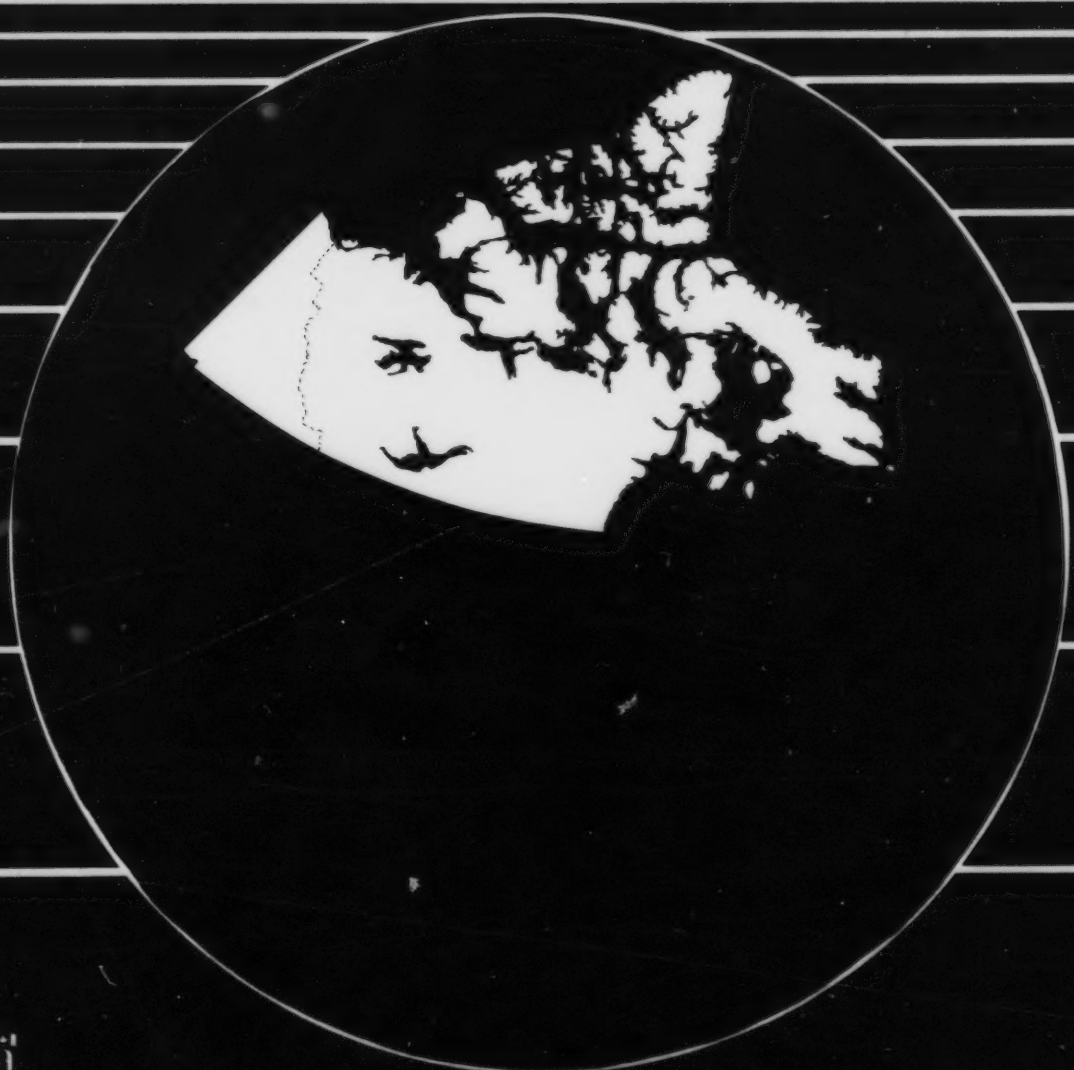
Environmental Studies No. 62

Groundwater Resources Protection From Drilling Waste, Northwest Territories and Yukon



Canada

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Groundwater Resources Protection From Drilling Waste, Northwest Territories and Yukon

Northern Affairs Program

Piteau Engineering Ltd.

August 1988

Published under the authority of the
Hon. Pierre H. Cadieux, P.C., M.P.,
Minister of Indian Affairs and
Northern Development,
Ottawa, 1989

QS-8439-000-EF-A1
Catalogue No.R71-19/62-1989E
ISBN 0-662-17183-7

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This Report was prepared under contract for the Water Resources Division,
Natural Resources and Economic Development Branch, Department of Indian and Northern Development.

The views, conclusions and recommendations expressed herein are those of the authors and not necessarily those of the Department.

90-00444/

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FIGURE 1: GEOLOGICAL/PHYSIOGRAPHICAL REGIONS OF NORTHERN CANADA - FOLLOWING PAGE 6

FIGURE 2: PERMAFROST IN CANADA - FOLLOWING PAGE 13

SUMMARY

Groundwater is a valuable, renewable natural resource. In the Yukon and Northwest Territories, due to an abundance of surface water and low population density, demand for groundwater is relatively low. As a result of these circumstances, in the past little emphasis was placed on proper development and protection of groundwater resources.

Approximately 1600 oil and gas wells were drilled in the Territories. Each well drilling operation produces substantial volumes of liquid and solid wastes. Some of the wastes produced may have a toxic character. Realization that the northern environment is sensitive to industrial activities led to a number of research projects related to oil and gas operations. This includes assessment of the potential impacts of drilling waste disposal on groundwater resources.

Information collected in the course of this study indicates that drilling waste disposal in sumps, downhole or on land, has not created major environmental damage to date. There are less than twenty documented cases where loss of mud or seepage from a pit has negatively affected groundwater quality within the active layer.

Downhole disposal of drilling wastes is not common in northern Canada. Logistical and technical difficulties associated with permafrost and low ambient winter temperatures make this option unattractive. There is no information that would describe a single incident of groundwater contamination originating from either downhole disposal of drilling wastes or improper abandonment of exploration wells.

Existing legislation and regulations concerning protection of water resources (including groundwater) against pollution from oil and gas

activities appear to be adequate at this time. It should also be noted that oil companies have their own regulations, which are rigorously followed by the companies involved in exploration activities.

RÉSUMÉ

Les eaux souterraines constituent de riches ressources naturelles renouvelables. Cependant, au Yukon et dans les Territoires du Nord-Ouest, l'abondance en eau de surface et la faible population éliminent presque la demande en eaux souterraines. Or, dans le passé, on n'a guère attaché d'importance à la mise en valeur et à la protection de ces ressources.

Dans les Territoires, on compte environ 1 600 puits de gaz et de pétrole. Lors de chaque opération de forage, des quantités notables de déchets solides et liquides sont produits et certains d'entre eux risquent d'être toxiques. Prenant conscience du fait que l'environnement du Nord est fragile face aux activités industrielles, le gouvernement a entrepris des recherches sur les activités pétrolières et gazières. Il a, entre autres, évalué les répercussions possibles de l'élimination des déchets de forage sur les eaux souterraines.

Les données recueillies jusqu'à présent révèlent que l'élimination des déchets de forage dans des puisards, au fond des puits ou à la surface du sol n'a pas nui sérieusement à l'environnement. Il y a moins de vingt études de cas étayées où l'on a relevé que de la boue et du pétrole s'étaient échappés d'un puisard et avaient détérioré la qualité des eaux souterraines logées dans le mollisol.

L'élimination des déchets de forage au fond des puits n'est pas très fréquente dans le Nord du Canada. En effet, les difficultés d'ordre technique et logistique liées au pergélisol et aux basses températures ambiantes en hiver ne favorisent pas un tel procédé. Toutefois, aucune donnée ne permet d'attribuer des incidents de contamination des eaux souterraines à l'élimination de déchets de forage dans des puisards ou à l'abandon de puits d'exploration.

Pour l'instant, les lois et les règlements en vigueur sur la protection des ressources en eau (y compris les eaux souterraines) contre la pollution causée par les activités pétrolières et gazières semblent convenables. Il importe également de souligner que les sociétés pétrolières imposent elles aussi leurs propres règlements, auxquels se conforment d'ailleurs à la lettre les entreprises oeuvrant dans le domaine de l'exploration.

ACKNOWLEDGEMENTS

Piteau Engineering greatly appreciates the opportunity to work on a study initiated by the Natural Resources and Economic Development Branch of the Northern Affairs Program of INAC and the information provided by members of Federal, Territorial and Alberta government agencies. We further acknowledge contributions from oil companies, drilling fluid manufacturers and distributors and the Canadian Petroleum Association. These contributions included personal communications and access to materials relatedm to drilling waste disposal.

We especially wish to thank Dr. V. Schilder of INAC for technical assistance and support during the course of this study. He was always available for discussion and generously shared his knowledge on water resources occurrence and protection in the Canadian north. The authors would like to acknowledge contributions from DIAND personnel: Mr. G. Whitley; Mr. D. Milburn; Mr. J.N. Jasper; Ms. D. Stewart; Ms. A. Snider; Mr. H. Madill; Mr. B. Grey; Mr. A. McKinnon, who reviewed the manuscript and made many valuable comments. Mr. R. Creasey of ERCB provided helpful advice on drilling practices in Alberta and critically reviewed the draft report.

Mr. F.B. Claridge, P. Eng. and Mr. L.J. Franklin, P. Eng. provided significant input in the areas of permafrost technology and arctic drilling operations, as well as a general review of the report.

1. INTRODUCTION

1.1 GENERAL

The processes of groundwater pollution are determined by the nature of the contaminants and the hydrogeological regime into which they are discharged. In many regions of the Yukon (YT) and Northwest Territories (NWT), the presence of permafrost creates a potential for pollution of groundwater different from that common in temperate climates.

The discovery and initial recovery of oil and natural gas reserves in northern Canada and northern Alaska in the 1920's, followed by expansion and development in the 1960's, subsequently led to hydrogeological studies conducted as a part of environmental impact assessments. In these studies, particular emphasis was placed on the role of groundwater in the freeze-thaw cycle. This factor is critical in foundation design and could also affect proposed developments in other ways (eg. structural integrity and slope stability). Initially, less emphasis was placed on groundwater as a source of water supply. Despite this limitation, appreciable knowledge of groundwater occurrence in unconsolidated and bedrock deposits was accumulated over the years.

Oil and gas exploratory drilling produces substantial volumes of liquid and solid wastes. As these wastes may be toxic, environmental damage may be caused if they are not appropriately managed. Experience gained has led to the realization that the northern environment is sensitive to any terrain disturbance. This sensitivity poses unique problems for both technical and environmental aspects of hydrocarbon drilling operations.

Expected continuous development of the northern areas will lead to a gradual increase in demand for dependable, year-round sources of water supply. In permafrost regions, groundwater may satisfy much of the potential need. In addition to water-supply potential, groundwater maintains winter flow in many northern rivers and streams, which is critical for survival of fish.

Considering the above, every measure should be undertaken to protect groundwater resources from any adverse effects of northern developments. This would include groundwater quality protection from potential contamination by drilling waste disposal in sumps or deep injection wells.

Contaminated groundwater clean-up operations in temperate climatic zones are very expensive and time consuming. In fact, the damage may be occasionally irreversible. The cost and technical problems associated with contaminant recovery from groundwater-bearing zones in a northern environment would likely exceed those of a similar operation in temperate climates. To avoid repetition of mistakes which have occurred in the past across the world, emphasis should be placed on protection and prevention rather than mitigation and remedial action.

The variety of drilling wastes (fluids and solids), their properties (toxic and non-toxic), and the number of different containment/disposal methods, combined with largely unknown (and variable) hydrogeological conditions, makes this study on groundwater resource protection a challenging task. The study compiles the existing information on this subject through literature review and interviews with government and oil industry personnel, and identifies hydrogeological information deficiencies for northern regions, and research needs.

1.2 STUDY OBJECTIVES

The objectives of the study were:

1. To evaluate ways of improving the design, construction, operation and abandonment of drilling waste sumps, thus promoting a reduction in the potential for groundwater contamination;

2. To evaluate the downhole disposal method of drilling wastes and its implications on the quality of groundwater resources; and,

3. To evaluate the information base and research requirements for groundwater in the areas with high hydrocarbon potential or proven reserves.

Piteau Engineering performed a literature search and conducted interviews with government employees, oil industry representatives and drilling mud manufacturers. Lists of contacts are given in Appendix I.

1.3 SCOPE OF WORK

The scope of work included the following tasks:

Topic: Sumps (SW 3.1)

Task (a) review literature on the use of sumps for drilling waste containment with respect to their impact on groundwater;

Task (b) consolidate the information on use of the sump disposal method for drilling wastes, and the current practices in other

jurisdictions, specifically in other cold regions such as Northern Alberta, Northern B.C. and Alaska;

Task (c) review past and current practices of sump disposal in the Northwest Territories and the Yukon;

Task (d) evaluate current practices identified in (b) and (c), as they relate to the disposal of drilling wastes in sumps; and,

Task (e) recommend improvements to the current design, operation and abandonment of sumps containing drilling wastes.

Topic: Deep Well Disposal (SW 3.2.)

Task (a) review the literature on use of the deep well disposal method for drilling wastes as it relates to groundwater contamination;

Task (b) consolidate the information on use of deep well disposal of drilling wastes, and current practices in other jurisdictions, specifically in other cold regions such as Northern Alberta, Northern B.C. and Alaska;

Task (c) review past and current practices of deep well disposal in the Northwest Territories and the Yukon;

Task (d) evaluate current practices identified in (b) and (c) as they relate to the disposal of drilling wastes into deep wells;

Task (e) recommend improvements to the current design, operation and abandonment of deep wells, which will help minimize the potential for groundwater contamination; and,

Task (f) identify information deficiencies in the current knowledge base with respect to the potential for groundwater contamination from deep well disposal and recommend research to address such gaps.

Topic: Data Base on Groundwater (SW 3.3)

Task (a) consolidate and review the literature on the groundwater resources in regions of hydrocarbon potential in the Northwest Territories and the Yukon;

Task (b) provide an assessment of the potential risk of groundwater contamination from both sump and deep well disposal methods in these regions; and,

Task (c) identify the information needs, with respect to groundwater in these regions, which will assist in providing better environmental protection measures for drilling waste disposal.

2. REGIONAL CHARACTERISTICS

2.1 AREAS OF HYDROCARBON POTENTIAL

Oil and gas exploration in Canada north of 60° has a relatively long history. It started with the 1924 Norman Wells discovery. Very high costs coupled with logistical difficulties limited exploratory drilling to the southern area of the Territories. In the late 1960's and early 1970's, the focus of exploration drilling shifted into the Mackenzie River Delta and Arctic Islands area. The distribution of oil and gas discoveries, and the potential for future discoveries in various geological provinces, can be found in Indian and Northern Affairs Canada (INAC, 1981) and the annual summary of activities of Canadian Oil and Gas Land Administration (COGLA, 1987).

Oil and gas discoveries, and promising exploration areas, extend over large parts of the Yukon and Northwest Territories, covering the following principal physiographic regions: Cordilleran, Interior Plains, Arctic Coastal Plains and Innuitian and Arctic Lowlands (Geological Survey of Canada (GSC), 1969; and 1981). The location of these regions and basins, where hydrocarbons may occur, is shown on Figure 1.

2.2 GEOLOGY

Geological and geophysical exploration programs led to hydrocarbon discoveries in the Territories. Extrapolation of the exploration results led to the conclusion that the following geological provinces offer potential for hydrocarbon discovery.

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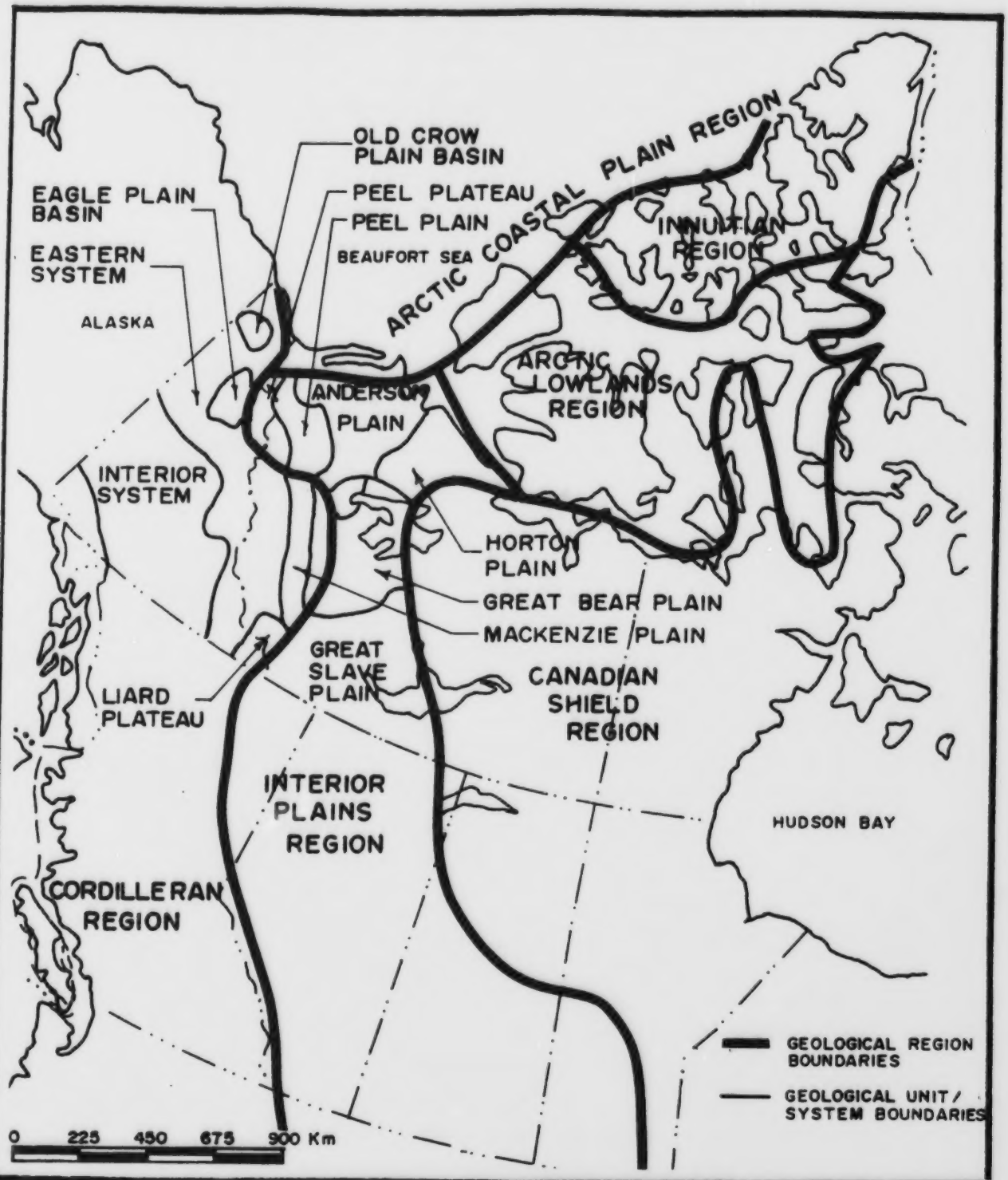

INDIAN AND NORTHERN AFFAIRS CANADA
SUMP AND DOWNHOLE DISPOSAL OF WASTE DRILLING FLUIDS

PITEAU ENGINEERING LTD.
GEOTECHNICAL AND HYDROGEOLOGICAL CONSULTANTS
VANCOUVER CALGARY

GEOLOGICAL / PHYSIOGRAPHICAL REGIONS OF NORTHERN CANADA

BY	DATE
M.T.	AUG. '88
APPROVED:	FIGURE
	1

2.2.1 Cordilleran Region

The Interior System consists of folded and faulted sedimentary, volcanic and metamorphic rocks with numerous igneous intrusions. Within this system only the Whitehorse Basin, located at the northern end of the Central Cordilleran Geosyncline, is considered to have some potential for hydrocarbon occurrence within an up to 4,500 m thick sequence of late Triassic to early Cretaceous sediments.

Quaternary deposits present in the area represent the following:

colluvium - a veneer of soil originating from bedrock weathering processes.

fluviatile deposits - present along river and stream courses, these are represented by silt, sand and gravel. Locally they may be covered by organic deposits. Their thickness can range from less than 1 m to more than 50 m.

Lacustrine and glacial deposits - these may be present locally.

The Eastern System includes Porcupine Mountain and Mackenzie Mountain physiographic areas. These mountains are almost entirely built of folded and faulted sedimentary rocks.

The Porcupine Mountain Area covers the Porcupine Plateau, which in turn includes two sedimentary basins. These are:

a) Old Crow Basin - is filled with Paleozoic, Mesozoic and Cenozoic clastic and carbonate sediments, with total thicknesses ranging from 3,000 m to over 4,500 m.

The bedrock formations are covered by surficial sediments. The most dominant in this area are lacustrine deposits (up to 50 m thick) represented by clay, silt, sand and gravel. Locally these sediments are intersected by river valleys which are filled with fluviatile deposits. Colluvium and fluviatile fans are present locally around the basin perimeter (GSC, 1971).

b) Eagle Plain Basin - consists of a sedimentary sequence which is similar to that of the Old Crow Basin. However, this succession can attain a thickness exceeding 6,000 m. Significant hydrocarbon shows have been encountered in this basin but no commerical discoveries have been announced.

There is little information available on the types (lithology) and thicknesses of the Quaternary deposits. Nevertheless, it may be expected that colluvium, fluviatile and lacustrine deposits will be prevalent.

Within the Mackenzie Mountain area, commercial quantities of oil and gas were discovered in the Mackenzie Plain (Norman Wells) and Liard Plateau (Pointed Mountain).

c) Mackenzie Plain - The Precambrian rock is overlain by a 1,200 m to 2,700 m thick sequence of Lower and Middle Paleozoic strata. These are in turn covered by Cretaceous or Tertiary strata. At Norman Wells, oil is produced from coral and stromatoporoidal limestone which form local reefs, up to 120 m thick. These structures are known as the Kee Scarp Member of Upper Middle Devonian (GSC, 1987).

Bedrock in this area is covered by glacial, alluvial and glacio-lacustrine deposits. Total thicknesses of these deposits within the Mackenzie River valley may exceed 30 m. The till is a clayey mixture of silt, sand and gravel. Alluvial deposits may range from fine-grained (clay/mud) to gravel. The glacio-lacustrine deposits are mostly fine-grained material: clay, silt and clayey or silty sands (Isaacs, 1974).

d) Liard Plateau - is built of Devonian and Mississipian rocks, exceeding 1,500 m in thickness, covered by a thin Cretaceous sequence. Gas is produced from Middle Devonian carbonates in the core of the Pointed Mountain anticline (NWT) and Kotamelee anticline (YT). The Beaver River field (YT) produces gas from Mississipian sands.

Parts of the Liard Plateau are unglaciated. In these areas, fluviatile, colluvial and lacustrine deposits will represent the Quaternary sediments. There is very little information available on distribution, type and thickness of these deposits.

2.2.2 Interior Plains Region

Anderson and Horton Plains - the sedimentary sequence is represented by nearly flat-lying Lower and Middle Paleozoic strata (Cambrian, Ordovican, Silurian and Devonian). The northern part of the plains is covered by Cretaceous sediments. Thickness of the succession above the Precambrian increases with distance from the Shield and may exceed 2,500 m in the western and northern parts. Within the Anderson Plain, gas was discovered in

Cambrian sandstones, and hydrocarbon shows were observed in the Cretaceous deposits.

The Anderson and Horton Plains are covered by a sheet of glacial deposits consisting of hummocky, kame and end moraines. These deposits are usually rich in silt and clay. However, outwash sediments are also present, especially in the southeast part of the plain. At higher elevations, within the Horton Plain, bedrock is either exposed or only covered by a veneer of soil.

Alluvial deposits of considerable thickness are present along major rivers traversing the plains. These consist mainly of silt, fine to medium-grained sands and local clay and gravel lenses.

Peel Plain - geological conditions in this region are similar to the Mackenzie Plain. Paleozoic carbonate and clastic strata are covered by Mesozoic sediments in the southwestern part of the plain. Sedimentary sequences range in thickness from approximately 2,500 m in the NE to over 4,000 m in the SW. Hydrocarbon shows were encountered in Devonian carbonates.

Quaternary deposits are locally represented by glacial, glaciofluvial and fluviatile sediments of variable thickness. These are often covered by organic deposits.

The Peel Plateau - is built of Tertiary and Cretaceous clastic sediments which overlie Paleozoic shales and carbonates. This sequence ranges in thickness from 3,000 m in the east to over 6,000 m in the west. Hydrocarbon traces were encountered both in

Cretaceous and Middle Devonian deposits. The bedrock is covered by a thin layer of Quaternary deposits including hummocky moraine, glacio-fluvial sediments and drumlins. Fluviatile deposits occur in the river valleys.

Great Bear Plain - consists of sedimentary rocks of Ordovician to Devonian age, covered by a sequence of clastic deposits of Cretaceous age. The thickness of these deposits ranges from 0 m to over 1,500 m, moving from the east toward the west boundary of the plain. No hydrocarbon discoveries or significant shows are reported for this area.

Great Slave Plain - is built of Devonian strata overlain by Cretaceous deposits. The thickness of this sedimentary sequence ranges from 0 m in the east to over 3,000 m in the west. Gas was discovered in limestones and dolomites of Middle Devonian age. The character and thickness of Quaternary deposits in the plain varies greatly. It is predominantly represented by sediments of glacial origin (till, outwash). Fluviatile and lacustrine deposits are also common. Total thickness of the surficial deposits may locally exceed 100 m.

2.2.3 Arctic Coastal Plain Region

This region includes the Yukon Coastal Plain, Mackenzie Delta and Island Coastal Plain. In this region, Cretaceous and Tertiary age sediments overlie older (Devonian) deposits. The thickness of the sedimentary complex may exceed 5,000 m. In the Mackenzie Delta, hydrocarbon shows were encountered in Devonian carbonates, while major oil and gas discoveries are associated with sandstones of Lower Cretaceous and Tertiary age.

Quaternary deposits in the Yukon Coastal Plain are represented by hummocky moraine and fluviatile sediments in the river valleys. The Mackenzie Delta is occupied by recent alluvial deposits which overlie a complex sequence of deltaic and fluviatile-marine sediments of Pleistocene age. The Arctic Coastal Plain is covered by glacial, alluvial and marine sediments of variable thickness and lithology.

2.2.4 Innuitian Region

Petroleum industry exploration conducted to date concentrated in the Sverdrup Basin. The thickness of the sedimentary sequence, consisting of Paleozoic rocks covered by lower Pennsylvanian to Tertiary deposits, may exceed 7,000 m along the basin axis. Hydrocarbon reservoirs were discovered in sandstones of Triassic and Jurassic age.

The Quaternary geology varies greatly as a result of a complex of pre-glacial, glacial and post-glacial processes which modified the regional physiography. Frozen ground and lack of vegetation causes rapid surface runoff which erodes channels in bedrock and overburden. Subsequent alluvial deposition then occurs in valleys and as fans. Remnants of glacial and marine deposits are common at some locations.

2.3 PERMAFROST

The thickness of permafrost in the discontinuous zone varies from less than a few metres at the southern limit up to about 100 m at the northern boundary. In the continuous zone, permafrost thickness ranges

from about 60 m to more than 700 m (Johnson, 1981). Judge (1973) predicted that the maximum permafrost thickness may exceed 1,000 m. Distribution of permafrost in Canada is shown on Figure 2.

The active layer thickness ranges from about 0.25 - 1.0 m in the continuous zone and from 0.5 - 3.0 m in the discontinuous zone. The condition and characteristics of permafrost at a particular location are controlled by a variety of factors including vegetation, topography, snow cover, surface drainage conditions, slope aspect, soil and rock types and ground temperature. The vegetation cover is the main component of the ecosystem which insulates the permafrost from extensive thawing during the summer. Discontinuous permafrost is present in the southern parts of both the NWT and the Yukon. Where unfrozen geological formations are present, conditions similar to those present in Northern Alberta and Northern B.C. can be expected.

Removal or disturbance of the vegetation cover and organic mat in permafrost areas deepens the active layer and thaws the permafrost. Introduction of water, as in the case of drilling fluids disposal in an excavated sump, upsets the thermal balance, causing absorption of solar radiation with subsequent thawing of the permafrost. The potential effects of the different compositions of drilling wastes on various permafrost materials, and hence on the surrounding terrain, will be addressed in this study. Of concern is the effect on the stability of the excavated slopes and the extent of slope regression and thermokarst development that may occur (Claridge and Mirza, 1981).

2.4 HYDROGEOLOGY

The northern hydrogeological region includes territories north of the southern limit of discontinuous permafrost (Brown, 1968). This vast

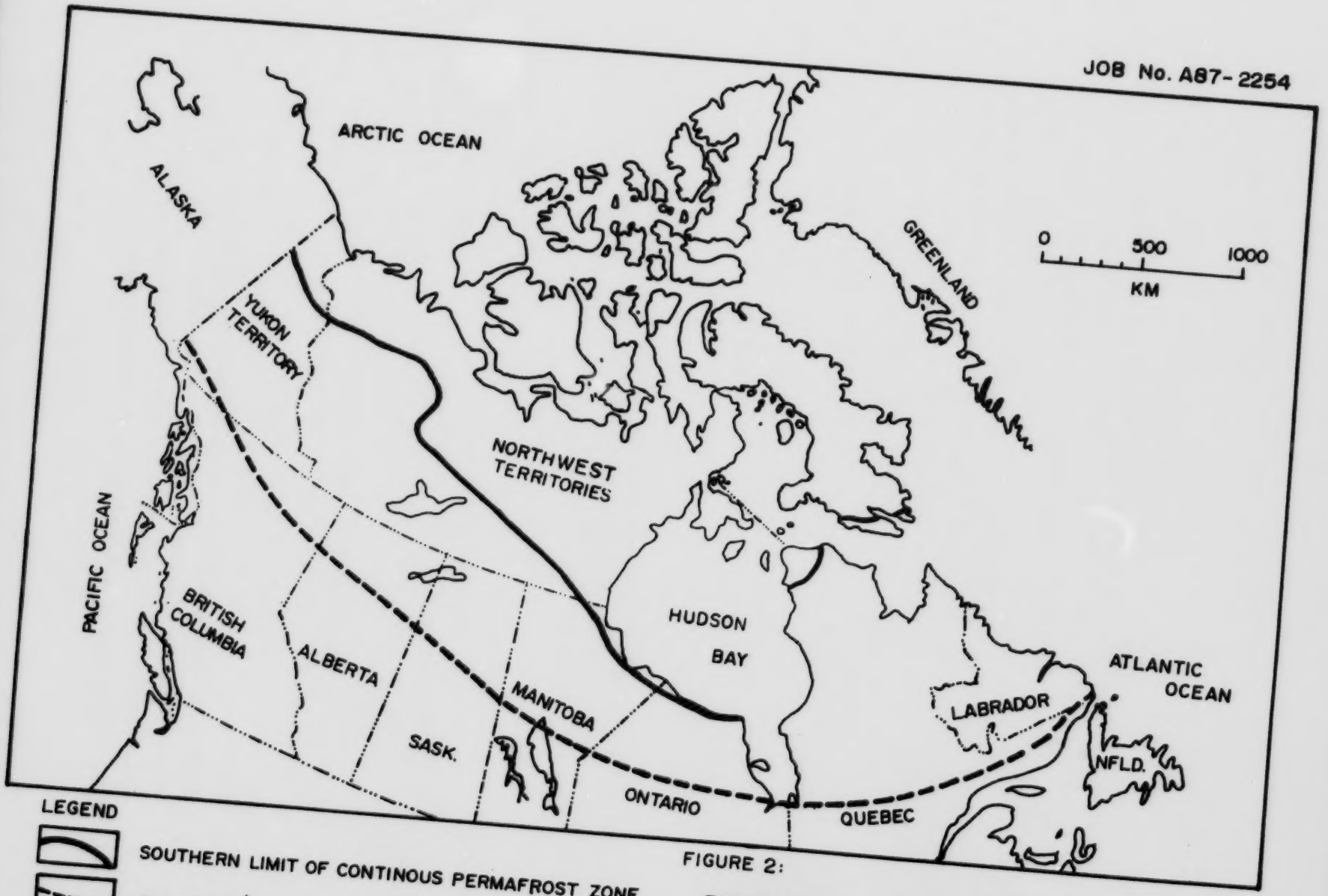

FIGURE 2:

PERMAFROST IN CANADA

(Modified after Brown and Péwé, 1973)

region covers terrains characterized by different climatic, physiographic and geologic conditions. It is not possible, due to a lack of hydrogeological data, to subdivide this region into smaller units.

Permafrost constitutes a low transmissivity layer, discontinuous along the southern limit of the Northern Hydrogeological Region and becoming continuous and thicker farther north. According to Van Everdingen (1974), permafrost has a significant but regionally and locally variable influence on:

1. recharge of deeper aquifers.
2. rates of groundwater movement.
3. spacial distribution of groundwater movement.
4. possibilities for groundwater discharge.

These factors have a direct impact on groundwater reserves and their quality.

A more recent study (Michel and Wilson, 1988), employing tritium as a tracer, demonstrates that permafrost acts as a low permeability layer which retards recharge and controls groundwater flow. Despite these restrictions, significant water movement within ice-bonded materials has been defined.

Occurrence of groundwater in the permafrost area differs from that in warmer climates. Tolstikhin (1941) distinguished three types of groundwater present in the permafrost. These are:

- suprapermafrost groundwater, occurs above the permafrost layer. It may include: groundwater contained in the active layer and groundwater present below the active layer;
- intrapermafrost groundwater, present within the permafrost; and,

- subpermafrost groundwater, stored below the lower permafrost boundary.

This classification does not address groundwater origin, geological environment, hydraulic properties of the host rock and circulation regime. Despite these limitations, Tolstikhin's classification is commonly accepted and used in hydrogeological studies related to permafrost areas. It is also very well suited for a study related to drilling waste disposal practices.

2.4.1 Suprapermafrost Groundwater

Seasonal freezing and thawing of the active zone makes it a unique type of intermittent groundwater-bearing zone. This zone is most exposed to potential contamination due to exploration/ production activities.

Groundwater recharge has a direct influence on groundwater reserves and circulation regime. A good understanding of this process, as applied to the continuous and discontinuous permafrost areas, has not been achieved and it is quantitatively not well defined. Few meteorological stations are located in this vast region, hence basic climatic information is sparse. Available measurements indicate that precipitation is low (less than 300 mm/year) in the majority of the NWT. It may exceed 500 mm/year) at higher elevations in the Cordillera (GSC, 1981; Barrie and Carr, 1988).

Recharge of groundwater stored in the active zone (suprapermafrost) may occur via infiltration of precipitation or seepage from adjacent surface water bodies during summer. Groundwater migrating from subpermafrost and intrapermafrost horizons may locally discharge into an active zone (Brown (1967); Michel and Wilson (1987)).

Studies conducted by Kane (1981) indicate that groundwater recharge, which can be attributed to rainfall and snowmelt, does occur in cold climates. However, the rate of recharge is expected to be small due to relatively low precipitation levels and low hydraulic conductivity of frozen rock/soil. Infiltration from surface water bodies, through hydrogeological windows (eg. taliks) is possibly a major contributor to intrapermafrost and subpermafrost groundwater- bearing zones.

Groundwater in the suprapermafrost zone usually has low mineralization. Elevated concentrations of organic substances, including humic and fulvic acids, are common in this zone; especially in low lying terrains. In general, groundwater from this zone has limited value as a source of water supply. Availability is intermittent within the thin active zone (frozen in winter). Groundwater in this zone may be easily polluted since it is usually close to the ground surface. Such vulnerability further reduces its potential as a source of water supply.

Despite the limitations listed above, suprapermafrost groundwater that occurs below lakes and rivers has been locally utilized by means of hand dug shallow wells in the Mackenzie River Delta (GSC, 1981; Brown, 1968; Brandon, 1965). Knowledge of the distribution of suprapermafrost water horizons is of great importance in construction planning and design, the operation and maintenance of roads, pipeline installation, building construction, and drilling site preparation due to potential heaving action, icing formations, flooding and terrain subsidence (Tolstikhin and Tolstikhin, 1974; Van Everdingen, 1974; Smith and Heinke, 1987; Johnson, 1981).

2.4.2 Intrapermafrost Groundwater

This term covers groundwater present in thawed zones (taliks) within permanently frozen soil or rock. Groundwater in this zone is not affected by seasonal changes, unlike water in the suprapermafrost. Rather it is controlled by long-term climatic changes (possibly over geological time).

Taliks occasionally occupy a fairly large area. They are commonly present below lakes, within large river valleys and along major structural features in mountainous regions. Often they act as a hydrogeological window between suprapermafrost and subpermafrost zones.

The chemical content of intrapermafrost water will depend on climatic and geologic factors as well as the circulation regime. In the active zone of groundwater exchange (eg. Cordillera), water quality may be very good, meeting potable water standards. On the other hand, groundwater which has been trapped for long periods within permanently frozen ground may undergo diagenetic processes, which may lead to an appreciable increase in mineralization. Taliks may also conduct groundwater with high total dissolved solids from deep sedimentary basins to discharge zones at the surface.

Intrapermafrost groundwater in the zone of discontinuous permafrost is commonly used as a source of water supply (Sherman, 1973; Kane, Carlson and Bowers, 1973). Many communities in the Yukon Territory depend on such wells as a main source of water (Brandon, 1965; Intera Environmental Consultants, 1975). In the

continuous permafrost region, taliks are expected to be less common and have smaller dimensions, thus they would be more difficult to locate.

2.4.3 Subpermafrost Groundwater

This term covers all water that occurs below the permafrost. Little information is available on groundwater occurrence, circulation and quality in regions with hydrocarbon potential in the NWT and YT.

Subpermafrost groundwater may be isolated from otherwise readily available recharge areas. In such cases, water exchange would be slow or very slow, thus contributing to an increase in mineralization. In general, however, it may be expected that subpermafrost groundwater would be of hydrochemical types similar to those encountered at comparable depths in analogous hydrogeological units in temperate latitudes. It is likely that rock type and chemistry, hydraulic properties, circulation regime, residence time and origin would have much greater impact on groundwater quality than low temperatures typical of permafrost regions.

Continuous and discontinuous permafrost terrains commonly have numerous lakes and ponds. Their role in the groundwater circulation regime was not fully understood in the past due to the lack of hydrogeological studies. Development of northern energy resources and associated exploration programs has led to documentation of the existence of unfrozen zones below some lakes. Through such hydrogeological windows, subpermafrost groundwater may recharge lakes (Kane and Sloughter, 1973).

Subpermafrost groundwater is often used as a supply source for small communities in the discontinuous permafrost zone in YT. No information on this subject is available for the NWT.

3. DRILLING FLUID SYSTEMS AND EFFLUENT CHARACTERISTICS

3.1 FLUID SYSTEMS

The primary functions a drilling fluid must serve for drilling in colder regions are very similar to those of warmer climates, namely:

- transport cuttings up the annulus;
- cool and clean the drill bit;
- reduce friction;
- provide stability for uncased boreholes;
- prevent the inflow of fluids (oil, gas, water) from a permeable or fractured zone; and,
- provide a thin filter cake on the borehole wall to seal pores and other openings in formations penetrated by the drill bit.

Design of a drilling mud system which provides all of these functions depends primarily on the geological profile. According to a number of drilling mud suppliers, on land the three most frequently used systems in the northern regions of Canada are, in order of decreasing useage:

- fresh water based;
- brine based; and,
- oil based.

The drilling fluid system used in a drilling operation should also meet the following criteria:

- be environmentally acceptable;
- minimize well completion costs;

- not interfere with the productivity of the fluid-bearing formation; and,
- not corrode or cause excessive wear of drilling equipment.

In response to growing concern regarding environmental protection, drilling fluid systems manufacturers are conducting research and extensive testing prior to new product introduction.

Methods for sampling and analysis of waste drilling fluids are given by Soniassy (1982). A detailed description of the composition and properties of drilling fluids can be found in: Robichaux (1975), Gray and Darbey (1980), Chilingarian and Vorabutr (1981), Moseley (1985), N.C. Baroid (1983), Soniassy (1983), World Oil (1984), Lloyd (1985) and Deebey and Canter (1985). A summary of information on drilling fluid systems and components used in Alberta and Saskatchewan is given by Petrology Consultants (1986) and Abouguendia, Baschak and Godwin (1985), respectively.

3.1.1 Fresh Water Based Systems

These systems are typically used in holes drilled to no greater than 2,000 metres in depth. The major component is generally a bentonite clay; hence these systems are usually called fresh water/gel mud systems. In order to satisfy all of the primary functions of a drilling fluid, a number of additives are often mixed with the fresh water based mud system.

Frequently used additives in fresh water/gel systems are soda ash ($NaCO_3$), caustic soda (NaOH) to control pH and remove calcium, lime (CaOH) to act as a flocculating agent, lignosulphonates to

reduce viscosity, barite to increase mud density and finally sawdust to control dowhhole loss of mud circulation. Biocides, lubricants and surfactants are often used on an as-required basis.

The exact composition of drilling fluids varies greatly from region to region, from well to well and even within an individual well. Mud engineers may constantly modify the properties of a drilling mud to meet specific downhole conditions (McCourt et al, 1984). It should be noted that oil is used in water based muds quite often to form an oil mud emulsion. Accordingly, the problem of oil contaminated mud disposal may exist for all mud systems.

3.1.2 Brine Based Systems

These systems are generally used for wells deeper than those where fresh water based systems are adequate. Typically they contain potassium chloride, bentonite, cellulose polymers, lignosulphonates and sodium hydroxide. The brine (salt water) allows for circulation of a colder drilling fluid, which is necessary when drilling through areas of permafrost. Potassium chloride lowers the freezing point of the mud system so as to reduce any possible thermal damage to permafrost (ie. well wash-out). The bentonite in this system is used as a viscosifier, to increase mud density, promote hole stability and reduce filtration losses.

3.1.3 Oil Based Systems

Oil based muds are more expensive but are used because they increase overall drilling efficiency. Lepine (1984), in a review paper mentions that oil based mud protects oil reservoirs that are water-sensitive. Also, oil based muds ease the release of the drill stem from tight spots and from differential sticking. The cuttings are larger and more consolidated due to the increased cutting speed, decreasing the fines present in the fluid (Andrews, personal communication, 1988).

A typical oil based mud commonly uses diesel fuel or crude oil, but where toxicity problems are evident, one may resort to use of a white mineral (paraffin) oil (Chenard, 1984). Initially, the major disadvantage to using a low toxicity oil, was lack of supply and high cost. Supply has increased with demand and presently these oils are produced by Esso and Shell in Sarnia and by Vista Chemicals in Houston (Bartlett, personal communication, 1988). Cost for low toxicity oil still remains higher than diesel by approximately 1.8 times (Hans, personal communication, 1988).

Most oil based drilling fluid is recovered for re-use, but the oil-coated potentially toxic rock cuttings must still be disposed of properly (Birchard, personal communication, 1988). Sump deposition of oil-contaminated fluids is generally prohibited. However, Ballantyne (1984) describes a partially successful attempt by Panarctic Oils Ltd. to dispose of oil based drilling fluids from a sump situated on Loughheed Island, NWT by insump (in-situ) incineration. The use of low toxicity oils for drilling

may increase disposal options and decrease disposal costs. This will make the cost of low toxicity oil less prohibitive.

Although oil based muds are at present infrequently used in NWT and Yukon (less than 1% according to Hardy BBT, 1987), by 1983 65% of development well drilling in the UK sector of the North Sea used oil based muds, and their use at the time was growing in the Norwegian sector (Johnston, 1984).

At present, large land based development programs have not been undertaken. If single platform multi-well drilling programs are started, oil based drilling fluids will be preferred for deviated well drilling (Hans, personal communication, 1988).

Options for treatment and disposal of oil based mud cuttings in the Canadian arctic are described in detail by Drinnan (et al, 1987).

3.2 DRILLING WASTE

Drilling waste is a complex and highly variable mixture, which may contain drilling and completion fluids, formation fluids, cuttings, waste cement and fluids from the everyday rig operation.

According to Hardy BBT (1987), appropriate criteria are not presently in place in the North to define chemical impacts and fluid toxicity.

Fluids in a sump are not uniform, and, especially during winter when sump fluids are frozen, it is difficult to get a representative sample. Determining whether decanting on land or into water poses an environ-

mental risk is difficult to assess. To obtain a representative sample from a sump in wintertime, Smith and James (1979) recommend weekly sample collection of waste fluid at discharge outlets throughout the duration of the drilling program. Analyses ought to include major ions such as sodium, potassium and chloride, as well as heavy metals commonly found in mud additives, for example, zinc, copper and chromium.

Recently, the United States Environmental Protection Agency (US EPA) decided not to regulate drilling mud and produced brine as hazardous wastes (Oil and Gas J., 1988). The EPA stated that present State and Federal regulation of oil and gas wastes appears to be adequate. The American Petroleum Institute (API), commenting on the EPA report, stated that their wastes are "high volume but low toxicity". However, in a study conducted in Alberta, it was found that 60% of nearly 600 sumps tested in 1983-84 showed signs of toxicity using either the 96-hour Trout Test or the Microtox Test (Energy Resources Conservation Board (ERCB, 1985).

Currently there is no standard method for environmental risk assessment of sumps in the Territories.

4. DRILLING WASTE DISPOSAL

In northern Canada, waste drilling fluids are mostly disposed of in sumps. Sump construction generally incorporates a natural or synthetic liner. Where oil based systems are used, the waste is either incinerated or disposed of in storage tanks for future use or removal.

The average onshore well, 3,049 m in depth, generated approximately 3.64 million litres (23,000 barrels) of waste drilling fluid (Bryant and Hrudey, 1976). Sampling, treatment and disposal of waste fluids from onshore drilling sites is described in general terms by Specken (1975, 1985).

4.1 DRILLING WASTE CONTAINMENT STRUCTURES (SUMPS/RESERVE PITS)

4.1.1 Siting

Several factors must be considered when choosing a sump location in a permafrost area. One of the most critical factors is the absence of ice lenses; exploration holes are drilled or test pits excavated to test for their presence. If ice is present in the material backfilled over top of the drilling fluids, it may later melt, causing subsidence and allowing penetration of heat into the sump (French and Smith, 1980). Other factors taken into account for sump site location are:

(a) gradient of the ground surface;
(b) high ground, siting away from drainage ways and at least 30 m from streams; and,

(c) avoidance of sites with groundwater close to the ground surface (Hardy BBT, 1987; Hardy BBT and Stanley, 1988).

In areas of discontinuous permafrost, a search is first made to find an ice-free location for sump siting. If permafrost is not detected, a site with an impermeable soil type is sought, preferably with no near-surface groundwater. Fluids frozen and buried in a winter operation may later thaw and increase the potential for generation and migration of contaminant. Sandy soils should be avoided. In areas of muskeg, sump locations remote from the drilling well are sometimes required by regulatory personnel.

In relatively warm, discontinuous permafrost, the ground is highly susceptible to thawing due to surface disturbances associated with the construction of a sump. If massive ground ice is present, as often is the case, for example in Mackenzie valley clays, extensive thermokarst development may occur, leading to slumping of the sides of the sump and submergence. Extreme care therefore must be exercised in locating sumps in warm permafrost where excess ground ice is present.

The Norman Wells oil field, operated by Esso Resources, is located in a discontinuous permafrost zone. For the development drilling program in the mid-1980's, several large sumps were located on the mainland in an area of clay soil types free of permafrost. In most cases, individual exploratory wells and sumps are designed to hold the drilling fluids from a single well. At Norman Wells, because much of the drilling activity occurs near or within the Mackenzie River, each sump received the

waste drilling fluids from a number of wells. One sump was required on Bear Island, situated in the Mackenzie River channel. Since the soil at this location was too permeable, an artificial liner was added to prevent infiltration of drilling fluids to the river (Sikstrom, personal communication, 1988).

HDPE liners were also utilized in the sumps placed on sand filled artificial drilling islands constructed in the Mackenzie River as part of the Norman Wells project (Claridge, personal communication, 1988).

In permafrost-free terrain, a number of factors have to be considered in selecting a suitable site for sump construction. These should include the following:

- site topography;
- distance to surface water bodies;
- depth to the groundwater surface; and,
- soil and geological conditions.

4.1.2 Types of Sumps

Drilling mud waste sumps are either re-circulating or non-circulating. To reduce the volume of a sump, some drilling operators practice re-use of sump fluids. In southern Canada this involves employment of a re-circulating sump. Because of low temperatures in the north, any re-use system must either be protected from freezing or restricted to summer operations.

Hardy BBT (1987) describes an enclosed system, used by NorthCor Energy Ltd. at their recently drilled well in the Liard Range north of Fort Liard, where terrain restrictions allowed for only a small sump. The procedure involved mechanical separation of solids, addition of a polymer and recentrifugation to remove fines. This system provided for re-use of 75% of the water. The system cost $3,000 per day to operate, which was calculated to be cheaper than using a remote (offsite) sump. Since most drilling in the northern regions takes place in winter, non-circulating sumps are far more common.

4.1.3 Sump Sizing

Determination of sump size is usually based on drillhole depth. According to Hardy BBT (1987) and Hardy BBT and Stanley (1983), Esso uses 1.3 m^3 sump volume per metre drilled at wellsites in the Canadian territories. In the north, Petro-Canada constructs 6,500 m^3 sumps into which they put 4,000 - 5,000 m^3 (25,000 - 30,000 bbl) of waste drilling fluids. Pedology Consultants et al. (1986), giving the Alberta situation, report requirements of only 0.5 m^3 sump volume per metre drilled.

In the north, all sumps must restrict drilling fluid levels to at least 1.2 m below the level of the immediately adjacent land (INAC, 1986). By maintaining this freeboard requirement, the fluids remain below the active layer in the permafrost, ie., that layer which thaws during the summer months.

According to Hardy BBT (1987), construction costs for sumps range from $14,000 in the southern NWT areas which are easily access-

ible, to $100,000 - $500,000 on less accessible coastal areas, the Mackenzie Delta and the High Arctic. In fact, a 100 m x 50 m x 5 m sump (the approximate size of a football field) costs $800,000 in the Arctic islands. Because of the high costs of sump construction and later rehabilitation, efforts to reduce the size of the sump by recycling, decanting, etc. are being made.

4.1.4 Sump Construction

Continuous Permafrost

In the continuous permafrost terrain, drilling and blasting usually precede sump excavation. Broken material is removed from the pit using bulldozers. Shell Canada sump construction manuals suggest the use of 2.4 cm thick preformed slabs of polyurethane foam insulation be placed against the sump walls and dykes (French and Smith, 1980). However, according to Mackenzie (personal communication, 1988) Gulf Resources Inc.'s attempts at insulating the permafrost with styrofoam placed inside the sump were unsuccessful.

Discontinuous Permafrost

In areas of discontinuous permafrost and permafrost-free terrain, use of bulldozers and other available earth moving equipment is common. Drilling and blasting is only employed when bedrock is encountered close to the ground surface.

Material excavated from the pit is stockpiled for eventual backfilling of the pit and reclamation of the area. Surface runoff in the sump area is diverted away from the pit. Details regarding sump construction procedures can be found in the Environmental Operating Guidelines (INAC, 1986).

4.1.5 Sump Operation

During drilling operations, only drilling fluids should be discharged to the sump. All other wastes from the camp and operation activities should be handled separately.

Keeping a good record of quantities and type(s) of mud used, including additives, is a sound practice at a well site. This information is essential for planning sump decommissioning. Other factors which should be considered are reduction of fluid volumes (when possible), prevention against soil thermal erosion and overfilling the pit. Guidelines regarding drilling fluid management and sump operation are given in a report by INAC (1986).

Most drilling operations use the fresh water-based mud system which will later freeze in a sump in winter conditons. The salt content, which may be occasionally high in drilling fluids, will depress the freezing point and cause an unfrozen layer to persist within the sump. Concentrated, unfrozen brine may later seep to the surface of sumps, posing an environmental problem (Mackenzie, personal communication, 1988).

Smith and James (1979) give a number of recommendations which should be considered when operating a drilling waste disposal facility in the High Arctic.

4.1.6 Drilling Site Abandonment - Sump Rehabilitation

During drilling site abandonment and reclamation, sump treatment may consist of one of the following (INAC, 1986):

- Squeezing;
- Trenching;
- Downhole Disposal;
- Decanting; and,
- Total Containment.

For summer drilling operations in nonpermafrost areas, the squeezing method has been used. In this method, the drilling wastes are mixed with excavated soil to form a thick-consistency mixture before burial.

Trenching has been tried in southern NWT but problems arise if the soils are wet (Hardy BBT, 1987). It can be done effectively only during summer months in ice-free soils which are able to absorb the fluid.

In decanting, sump fluid is first analyzed for its toxicity (requested by less than 10% of operators) and treated if needed, prior to decanting on land or to a water body (Hardy BBT, 1987; Hardy BBT and Stanley, 1988). French and Smith (1980) and French (1981) recommend land decanting as a viable disposal option for many parts of the Arctic.

Total containment is the current disposal method under the Land Use Regulations for the Canadian Territories (INAC, 1986). This method calls for the burial of drilling wastes in a sump with no decanting of liquids. In areas of continuous permafrost it is presumed that the frozen wastes remain immobile. Sump location is usually chosen in the fall, prior to winter drilling. Organic cover is removed and conserved for reclamation. The site is

blasted to a depth of 5.5 m and excavated. In winter, the drilling wastes are deposited in the sump below the active zone, allowed to freeze solid and then covered with the excavated material, forming a cap. The organic cover is replaced, the surface roughened to induce vegetation growth, and the soil seeded (INAC, 1986).

Processing/recycling of the drilling fluids has been used in the North a few times recently to reduce the fluid volume for disposal or to allow operation where sump construction is not feasible. Physical-chemical processes of flocculation and centrifugation are used to clean the water to allow recycling. Essentially dry solids are produced and the need for a sump is eliminated. Tankage is used for emergency liquid handling. The costs of treatment can be offset by reduced costs for sump construction, water handling and clean-up costs. This procedure is especially useful in reducing clean-up costs when KCl fluid systems are used. Treatment and disposal of drilling fluids is often impractical due to freezing of water during the Arctic winter (French and Smith, 1980). Processing/recycling of drilling fluids may become more common as the use of expensive polymer based muds becomes more widely accepted as has been noted recently in the United States (Wilder, personal communication, 1988).

4.1.7 Environmental Effects of Sumps in Various Regions

Hardy BBT (1988) conducted geophysical assessments of waste drilling fluid containment at selected sites in the Mackenzie River Valley region. Eight sites were surveyed using a Geonics EM 31 system. The results of the electromagnetic soundings indicated:

- one sump was rated as definitely leaking;
- two sumps were rated as having high probability of leakage;
- three sumps were rated as possibly leaking;
- one sump was rated as providing probable containment; and,
- one sump was rated as providing highly probable containment.

Following evaluation of the results, the authors provided general recommendations regarding sump location and further applications of geophysical surveys in sump siting and baseline data collection.

Smith and James (1985) monitored ecological changes adjacent to six wellsites located in the Mackenzie Delta (3 sites) and Peel Plateau (3 sites). Enrichment of soils in potassium, sodium and chloride was observed due to solute movement along the terrain slopes. Vertical percolation of these ions through the active layer at some locations was found as well. Leakage of salt-rich fluids caused widespread and severe damage to vegetation at some sumps while only minor damage was observed at other sites.

French (1981) performed geomorphological investigations at five abandoned well sites in regions of the northern Yukon Territory. He observed greater well site terrain disturbances in parts of the Mackenzie Delta and the Arctic Islands as compared to the well sites in the Yukon. French concluded that the differences probably reflect the generally lower terrain sensitivity of much of the interior Yukon Territory (similar to drill sites in Alaska) together with the relative rapidity of revegetation in the Yukon boreal forest-shrub tundra transitional zones.

French and Smith (1980) monitored sump geothermal conditions at two such wells (Cameron Island and Mackenzie Delta) in the N.W.T. during 1976-77. In a one-season winter operation, permafrost temperatures at the 0.25 m depth below the floor of the sump rose from -15 and -20°C before commencement of drilling, to -9°C during drilling. Temperatures of the frozen sump fluids at the end of drilling were -8°C. Sump filling took place before summer thaw, therefore it seems likely that the fluids remained frozen.

At a two-season winter operation at which the sump fluids were allowed to thaw during the summer, French and Smith recorded a temperature of +0.5°C on the sump floor during the late summer. Minimal thawing of the sump floor took place, however, thawing to a depth of 2.0 m occurred on the sump walls. French and Smith speculate that in areas of warmer permafrost temperatures, the influx of sump fluids may be sufficient to induce significant thermal degradation of the sump floor.

Before 1975, when summer drilling was more commonly practiced, sumps cut into the permafrost were often affected by thermokarst development. Lawson and Brown (1979) investigated thermokarst formations at former drill sites in northern Alaska and found that 28 years after initial drill site terrain disturbances, there was still an active thaw. The depth of thaw in the deepest thermokarst troughs at one former drill site exceeded 2 m. In contrast, undisturbed areas of the Alaskan upland surface typically were thawed between 0.2 to 0.5 m.

Smith and James (1979) monitored the effect of sump disposal on vegetation at six High Arctic well sites. They found an eradica-

tion of plants close to the sumps. Reductions in species numbers and abundance further downslope were noted. They were not able to determine whether the observed effects were due to chemical toxicity or simply attributable to physical disturbances of the area. They did, however, find elevated sodium, potassium and chloride content in plants and soils in disturbed areas. Elevated heavy metal concentrations were recorded in soils adjacent to sumps at some sites. Smith and James (1979) conclude, however, that this contamination was not a consequence of intrinsic sump failure but rather resulted from leaching and erosion processes associated with placement of sumps on high parts of the terrain, either on slopes or immediately adjacent to slopes. They recommend continued use of sumps for drilling waste disposal in the High Arctic, provided that topography is taken into account. Selection of the sump location should only be made after onsite inspection during the snow-free period so that natural depressions ideal for sump-siting can be found.

French (1979) analyzed 47 abandoned well sites in the Mackenzie Delta and Arctic Islands during 1976 and 1977. About 30% of the sites exhibited signs related either directly or indirectly to sumps and containment of the waste drill fluids. Site restoration usually leads to sump subsidence and collapse, noncontainment of fluids during sump infill, subsurface leakage of fluids, and terrain disturbance adjacent to the sump. One-season winter operations reduces this disturbance. Two-season winter drilling - in which the sump was left open during the summer - and one-season summer drilling operations were more susceptible to terrain damages. Although no trend was discernible regarding whether sump related disturbances decreased from 1970 - 77, the

increased awareness of land use inspectors and industry operators concerning environmental impacts suggests there may have been a decrease, a trend which, if real, may still continue.

In the North above the treeline, environmental conditions vary greatly. French (1978) suggests distinguishing between (a) low Arctic tundra (e.g. Mackenzie Delta), (b) high Arctic tundra (e.g. Banks Island, Southwest Cameron Island), and (c) polar desert regions (e.g. Prince Patrick Island). Significant differences in environmental sensitivity were related to duration and magnitude of summer thaw, vegetation cover, ground ice conditions, underlying geology, and accessibility to aggregate sources. Operating conditions attached to land use permits ought to take into account these different environmental conditions.

French (1978) also reports on some differences between Alaskan North Slope conditions and those experienced in the Canadian territories. Alaska has had better success in site restoration. This may be due to a greater availability at Alaska drill sites of aggregate sources for sump in-filling (in-filling with frozen conglomerate material is not as effective as unfrozen). As well, most Alaskan drilling is shallower and encounters less complex geological conditions in comparison with Canadian drill sites. In Canada, the deeper wells require greater volumes of drilling fluid/mud, and drilling fluids are of a more complex chemical composition.

4.2 DOWNHOLE DISPOSAL

Although downhole disposal is not a common solution, it has been used in the High Arctic and involves pumping the clean water and low solids portion of drilling fluids into the drilling hole (Hardy BBT, 1987).

According to the American Petroleum Institute (1987), liquids which represent 63% of total drilling waste, are disposed in the USA by evaporation, followed by surface discharge, injection down the drilled well's annulus and hauling off site. Currently, downhole disposal of liquid drilling wastes is more commonly used in the USA than in northern Canada.

According to the available information, there is only one injection well operating in the NWT and Yukon. This is located in the Pointed Mountain (NWT) Gas Field and it is used for re-injection of produced water.

4.3 LAND DISPOSAL

There is very little available information regarding drilling waste containment/disposal for exploration holes drilled prior to the introduction of the Territorial Lands Act. It may be expected that in many instances, sumps were left open, or their contents discharged on land or into the surface drainage system. Often, the old drilling sites cannot be identified on the ground surface. This may be an indication of limited or short-term environmental damage. However, when filled with water, sumps can be difficult to distinguish from naturally occurring ponds and lakes.

Land disposal in many cases also left no obvious signs of damage. However, it should be noted that in the past, the drilling muds used were mostly fresh water based and contained few additives. They were therefore of comparatively low toxicity. This observation regarding old sites led to renewed interest and experiments with on land disposal of drilling wastes.

In the winter of 1981-82 at a drilling location in the polar semi-desert region of the High Arctic an experiment was conducted to determine the physical and biological effects of surface disposal of waste drilling fluids. Extended monitoring of the site has been recommended and is proceeding. Preliminary examination of the site in the summer of 1982 indicated that:

a) the sumpless operation caused no apparent significant deleterious changes in water quality in the adjacent drainage system;

b) botanical growth was normal in the areas adjacent to the mud disposal zone;

c) terrain disturbance was substantially reduced from that which would have occurred if a sump had been constructed.

The sumpless surface disposal of drilling wastes, exhibiting reduced environmental disturbance plus attractive cost reductions for the operator, may be an attractive procedure in the polar semi-desert areas at least, and worthy of further examination for use in other areas.

5. REGULATIONS RELATED TO DRILLING WASTE DISPOSAL

5.1 NORTHWEST TERRITORIES AND YUKON TERRITORY

The following is a list of acts and regulations related to the oil industry and applicable to waste management procedures.

LANDS

Territorial Lands Act - Territorial Land Use Regulations

These Regulations are derived from the Territorial Lands Act and provide for the issuance of permits authorizing companies or individuals to carry out specific land use operations at specified times and locations. Conditions are appended to the permits detailing how wastes associated with the particular land use operation must be disposed. Section 31 (g) of the regulations governs the use, storage, handling and ultimate disposal of any chemical or toxic material to be used in the operation.

Public Lands Grants Act

This Act provides for the disposition of federal Crown land not already under other legislative control. Leases and/or licenses are issued under the Act for disposition of lands and may contain any environmental conditions appropriate under other Federal legislation. The issuance of subsea leases and licenses for dredging and construction of berms or artificial islands is carried out under this Act. The lease usually has conditions attached detailing how and where wastes may be disposed of.

WATER

Northern Inland Waters Act - Northern Inland Waters Regulations

The purpose of the Northern Inland Waters Act (NIWA), and its accompanying Regulations, is to provide for the proper conservation, development and utilization of the water resources of the Yukon and NWT. The Regulations establish the procedures for licensing projects for the use of water or discharge of wastes into inland waters. A water licence is not required if the proposed use is for water engineering purposes (as defined in the NIWA), or the quantity of water used is less than 50,000 gallons per day. If a waste is to be deposited into inland waters a licence will be required. This requirement is reviewed on an individual basis. Allowable concentrations and volumes of waste to be discharged would be regulated as part of the licence requirements.

Arctic Waters Pollution Prevention Act - Arctic Waters Pollution Prevention Regulations

One of the primary purposes of this Act is to maintain the quality of Arctic Waters through the regulation of waste disposal into them. The Act applies to all Canadian Arctic Waters, as defined by the Act.

Section (4(i)) of the Act prohibits the deposit of waste on any area of the mainland or Arctic Islands where there is a possibility of it entering Arctic Waters.

The Arctic Waters Pollution Prevention Regulations allows for the deposition of industrial waste in Arctic Waters under terms authorized by

the Oil and Gas Production and Conservation Act, Territorial Lands Act, or the Public Lands Grant Act. Domestic waste may be discharged to Arctic Waters under conditions authorized by the NWT and/or Yukon Public Health Ordinance.

OIL AND GAS

Canada Oil and Gas Production and Conservation Act - Canada Oil and Gas Drilling Regulations

This Act provides for the control of all aspects of oil and gas exploration and development both onshore and offshore, including waste disposal. It is the principal statute by which oil and gas related activities are regulated and makes provision for the development of regulations to control drilling and production activities.

The Canada Oil and Gas Drilling Regulations cover disposal of all wastes from a drilling operation. The Regulations do not specify or identify approved methods but state that the disposal must be in a manner approved by COGLA.

Part 8 of the Draft Canada Oil and Gas Production and Conservation Regulations covers disposal of all wastes from oil and gas production operations. The Regulations outline conditions for disposal of wastes and require that disposal must be in a manner that does not create a hazard to the natural environment.

These regulations cover all the aspects of oil and gas drilling including:

- drilling program approval;
- authority to drill a well;
- authorized entry, inspection and investigations;
- drilling of a well;
- safety and training of personnel;
- operational records and reports;
- well evaluation;
- storage of samples from a well;
- final well reports; and,
- security and release of well information and materials.

OTHER

Environmental Protection Act (NWT)

This Act prohibits the discharge of contaminants, which includes odour, noise, heat and vibration to the environment. For the purposes of the Act, environment includes land, water, air and all plant and animal life of the NWT. It does not include the offshore. This Act is superseded by all federal legislation that authorizes discharges and contaminants. This Act is primarily used when the Federal Government chooses not to act on a discharge, but the Territorial Government does.

The Act makes provisions for the development of any regulations necessary to carry out the purpose of the Act. Regulations are currently under development and may be presented in the fall sitting of 1988. At present, there has been no regulation developed that might impact on the oil industry operations.

Administration of the Act is handled by the Pollution Control Division of the Department of Renewable Resources, Government of NWT.

Fisheries Act

This Act deals with all aspects of fisheries, including pollution control and is aimed at the protection, conservation and preservation of fisheries in Canada. Section 33 prohibits the deposit of deleterious waste in water frequented by fish in any place or under any conditions where such deleterious substances may enter such water. This section does not apply if the deposit of waste is authorized under another Act. However, if you exceed the limits authorized by the other Act you can then be held liable under the Fisheries Act, as well as the Act you were originally authorized under.

Section 33 of the Fisheries Act is enforced by the Environmental Protection Service (EPS) of the Federal Department of Environment.

5.2 ALBERTA

Exploratory drilling, production and well site activities in Alberta are regulated by the Oil and Gas Conservation Act and Oil and Gas Conservation Regulations. The Energy Resources Conservation Board (ERCB) is responsible for these activities under this Act. The ERCB is cooperating closely with the petroleum industry, Alberta Energy and Natural Resources (AENR), which is responsible for management of all the Crown-owned lands, and Alberta Environment (AE), which is responsible for large size projects (eg. Peace River, Cold Lake). Alberta Environment under the Clean Water Act, issues licences which impose conditions required to protect the environment.

The ERCB developed a set of guidelines called Interim Directive ID-OG 75-2. These guidelines addressed:

- disposal of sump fluids to a subsurface formation.
- disposal of sump fluids on the lease.
- disposal of sump fluids off the lease.

Disposal of sump fluids to a subsurface formation according to this guideline is an acceptable procedure provided:

- approval is first obtained from the ERCB;
- the receiving formation is not locally hydrocarbon productive;
- the formation water in the disposal zone has total dissolved solids (TDS) content greater than 20,000 mg/l.

In 1981, the ERCB brought out an Interim Directive (ID 81-1) concerning the subsurface disposal of drilling fluids. Conditions for this type of disposal are:

- permission from the Board;
- depth exceeding 600 m;
- formation water has TDS greater than 20,000 mg/l;
- the disposal zone must not contain hydrocarbons within 2 km of the well;
- injection procedures, for wells to be abandoned which do not contain at least 600 m of casing cemented in place;
- injection procedures, where a second casing has been run in a well and not cemented to the surface;
- injection procedures, where the disposal zone has been cemented behind the casing.

Additional surface casing and logging requirements for new disposal and injection wells are outlined in the ERCB information letter (IL 84-12). Geological, resource, well completion, operation and monitoring considerations for choosing subsurface disposal locations in Alberta are given by Berndtsson (1987).

Disposal of sump fluids on the lease according to ID-OG 75-2 is an acceptable procedure providing the following conditions are met:

- notice of at least one week must be given to AENR or ERCB, depending on well location;
- the entire contents of the sump are confined to the lease;
- the sump contains less than 6,000 barrels of fluid;
- the lease is more than 300 feet from the normal high water mark of a body of water or potable water well; and
- the lease site will accept the sump contents without runoff.

Disposal of sump fluids off the lease is acceptable providing:

- the sump fluids meet the following criteria:

Chloride Content	less than 1,000 mg/l
Sulfate Content	less than 2,000 mg/l
Total Dissolved Solids	less than 4,000 mg/l
pH	5.5 - 8.5
Trout Survival Test	3 trout fingerlings (4 to 10 mm in length) must survive 96 hours.

- approval from appropriate district office of AENR or ERCB is obtained;
- sampling and analyses are conducted according with procedures outlined in the guideline;

- disposal of well sump fluids to any surface water must be approved by AE.

In May, 1973, Alberta Environment, Standards and Approvals Division issued "Guidelines for Disposal of Oil Well Sump Fluids". This guideline has been superseded by ERCB directives.

Energy and Natural Resources, Information Letter 82-5 "Potassium Based Drilling Mud Systems" was issued in response to increased use of KCl muds by the drilling industry. No specific criteria for waste handling and disposal is given. This document recommends the submission of a disposal plan prior to the commencement of drilling. Subsurface injection as a disposal option for KCl muds is encouraged.

The "Guidelines for Sump Fluid Disposal on Crown Land - White and Yellow Areas" were developed following a transfer of responsiblity for surveillance of drilling waste disposal on public lands from the ERCB to the Public Lands Division of Alberta Energy and Natural Resources in 1983. It specifies the application for disposal procedures and regulatory requirements.

In July, 1987, Alberta Environment, Environmental Protection Services issued "Draft Guidelines for Land Treatment of Industrial Wastes". Acceptable for disposal along with other industrial wastes are oil field wastes that include pit cleanings. This guideline provides information required for design and operation of the facility as well as monitoring requirements.

Drilling waste disposal practices including surface spreading are discussed in detail by Lloyd (1985) and Pedology Consultants, et al (1986).

5.3 BRITISH COLUMBIA

In this province, the Petroleum and Natural Gas Act regulates all the activities related to oil and gas exploration, production and abandonment. The purpose of this Act and its accompanying regulations, is to provide for proper development and utilization of petroleum resources.

The Drilling and Production Regulations, Division 61, specify conditions required for Storage and Disposal of Drilling and Production Wastes. These are:

- The operator shall ascertain that the bottom of the pit has not reached groundwater level and that the pit is constructed in clay-type soil.

- Before the disposal, the operator shall obtain water and sludge samples and conduct a standard analysis or a special analysis as specified under B.C. Regulation 432/82 of the Waste Management Regulations, submit a copy of the analysis to the district office and obtain approval for the disposal of fluid waste and closure of the pit.

- The liquid wastes shall not be permitted to:
  (a) create a hazard to public health and safety;
  (b) contaminate a surface water body;
  (c) run over or damage any land, highway or public road; and
  (d) enter waters frequented by fish or migratory birds.

Procedures for lease clean-up given in the Guidelines for Construction and Clean-up of Roads, Leases and Seismic Lines in Petroleum Exploration Areas (British Columbia, 1985) include sump fluid sampling and fluid disposal to subsurface formation by pump-off, deep trenching, shallow trenching.

Sump fluid disposal to a subsurface formation where possible is encouraged by the B.C. Ministry of Energy, Mines and Petroleum Resources provided:

- approval is first obtained from the Petroleum Resource Division;
- disposal formation is deeper than 610 m and is acceptable to the Division; and,
- a complete report detailing the entire operation is submitted to the Division.

Disposal of drilling fluids by discharging them into surrounding area is acceptable provided:

- approval is first obtained;
- the area of disposal is identified; and,
- the sump fluids meet the following criteria:

hydrocarbon	nil
total suspended solids (flexible)	50 g/m^3
pH @ 20°C	5.5 - 8.5
chloride	less than 3,000 g/m^3
sulphate	2,000 g/m^3
potassium	1,100 g/m^3
calcium	500 g/m^3
magnesium	1,500 g/m^3
total dissolved solids	4,000 g/m^3
SAR	20
fish bio-assay	96 hour test with 100% survival

Use of deep and shallow trenching as well as trap and mix disposal is acceptable without stringent drilling fluids quality requirements.

Construction techniques are specified in the "Guidelines" (British Columbia, 1985).

Plugging requirements for test holes and wells, sealing of oil, gas and water wells are specified in the Drilling and Production Regulations, Divisions (7), (57) and (33), respectively.

Ward (1983) proposed standards and guidelines for the testing and monitoring of wastes contained in sumps from oil and gas well drilling operations in British Columbia. This paper describes sampling and analytical programs for British Columbia and Alberta.

5.4 ALASKA

The Alaska Division of Environmental Conservation (ADEC) and the US Environmental Protection Agency (EPA) regulate hazardous waste disposal. Matters related to drilling waste and oil field brine disposal are a joint responsibility of the Alaska Oil and Gas Conservation Commission (AOGCC), ADEC and EPA.

The AOGCC (1986) issued regulations which are a compilation of documents related to oil and gas activities in Alaska. The following is a summary of regulations on reserve pits (drilling sumps), injection wells and well plugging and abandonment.

Reserve pits must be constructed or appropriate tankage installed for the reception and containment of drilling fluids and cuttings, to facilitate the safety of the drilling operation and to prevent contamination of groundwater and damage to the surface environment.

Following termination of operation at the well site, the operator is responsible for disposal or solidification in place of all pumpable fluids. The abandoned reserve pit must be in a condition that does not constitute a hazard to groundwater.

Disposal of fresh water, salt water, brackish water or other oil field waste fluids is prohibited except when approved by the Commission in response to an application for injection.

Well abandonment and plugging requirements are specified in AOGCC Regulations (1986), Article 2. The objective of each operation is to prevent the movement of liquid or gas between formations or within the well bore.

6. INDUSTRY GUIDELINES

6.1 CANADIAN PETROLEUM ASSOCIATION

Increasing awareness and growing concern regarding environmental protection has led the Canadian Petroleum Association (CPA) to develop industry guidelines for different activities related to exploration, production, transportation and hydrocarbon processing. Guidelines and studies sponsored by CPA provide scientific and practical information for operators and technical personnel involved in the planning, design and operation of different facilities.

The Canadian Petroleum Association (1987) developed guidelines for drilling sump construction. Its main objective was to ensure adequate protection of the surrounding environment. Although these guidelines have been designed for sump construction in Alberta, it is expected that a knowledge of local conditions in other regions would allow adoption and modification of proposed procedures. According to the recommended guidelines, sumps should be excavated in an impervious clay-till to prevent loss of drilling fluid and potential contamination of groundwater. When foundation conditions are not suitable for sump location, construction of a natural or artificial liner may become an alternative solution.

The Environmental Planning and Management Committee of the CPA (1984) developed "Waste Disposal Guidelines for the Petroleum Industry". These guidelines describe preferred acceptable methods, and identifies unacceptable methods for disposal of conventional water based fluids, KCl

fluids and oil based or invert muds. Methods described in this document conform with the regulations described in Chapter 5 of this study.

6.2 AMERICAN PETROLEUM INSTITUTE

In the US, the EPA is responsible for assessment of petroleum exploration and production wastes and their potential impact on human health and environment. To address these issues, the American Petroleum Institute (1987) commissioned an independent study.

According to this study, thirty-five percent of all reserve pits (drilling sumps) are constructed with a synthetic liner. Drilling site reclamation includes disposal of liquids using one of the following means: evaporation, surface discharge, or downhole injection. Solids represent only a small fraction of total drilling waste and are landspread or buried on site. In environmentally sensitive areas, wastes are hauled off-site to a licensed disposal facility.

The API (1987) study indicates that there is very limited potential for contamination of groundwater from reserve pits. The low hydraulic conductivity of the mud (or liner, if present) retards leaching. Once a leachate flux enters the groundwater-bearing zone, it is being dispersed and contaminant concentrations reduced.

Despite these findings, the EPA recommends that environmentally "more acceptable" alternative waste management practices be developed and implemented by the petroleum industry.

7. IMPACT OF PRESENT DRILLING WASTE DISPOSAL PRACTICES ON GROUNDWATER RESOURCES

7.1 GENERAL ASSESSMENT

Groundwater seepage/movement in most instances is quite slow and as it occurs below the ground surface, it is not readily visible or detectable. It may take a very long time for a contaminant to move from the storage/disposal area to a water-supply well or discharge zone where it can be detected. To give an impression of the order of magnitude of natural flow rates, the following example is given. If the groundwater surface elevation declines by 100 ft in one mile (i.e. 19 m/km) this gives a hydraulic gradient, i = 0.019; and if a moderate permeability (hydraulic conductivity) is selected for fine sand, k = 1 m/day; and a typical effective porosity is 25%, then the average real flow velocity would be 28 m per year. Hence it would take about 35 years for the groundwater to travel 1 km. In a moderate-yielding aquifer of hydraulic conductivity k = 10 m/day, the groundwater would take about 3.5 years to travel 1 km.

There is only limited information available on the potential impact of drilling waste disposal on groundwater resources in the Canadian North. In order to provide a background for the regional assessment, experiences gathered from drilling operations conducted in temperate climatic zones are briefly summarized in the following sections.

Contaminants originating from drilling wastes may enter the groundwater circulation system either dissolved in the water or as liquid phases that may be immiscible in water. Contaminant transport processess are

complex. They depend on a multitude of factors which are difficult to accurately define, especially in the field. These are: hydraulic properties of soil and rock (hydraulic conductivity, transmissivity, storativity and fracture geometry, which includes their dimensions, extent and continuity); hydraulic gradients - these control flow directions and velocity; and a number of physical and chemical processes having a strong influence on contaminant migration, eg. advection, dispersion (mechanical mixing and molecular diffusion), sorption and retardation processes, chemical and biological transformation.

Literature on hydrogeological processes controlling subsurface migration of contaminants is extensive and rapidly growing. This includes Campbell and Gray (1975), Gregg and Kennedy (1975), Grisak and Jackson (1978), Freeze and Cherry (1979), MacKay et al (1985), Canter (1985), Deeley and Whiteker (1986).

7.2 SUMPS

Drilling fluid loss from mud sumps may occur as a result of seepage through the pit bottom and walls, over-topping or breaching of the berm. Over-topping and breaching of the berm can be easily prevented by proper pit sizing and design. Seepage or leakage of fluids from the pit, even when modern lining techniques are applied, is difficult to completely eliminate.

Liquids seeping from a pit into groundwater-bearing zones form a contaminant plume. The plume is elongated in the direction of groundwater movement and usually is several times longer than it is wide. With increasing distance from the source of contamination (eg. sumps), plumes tend to become wider and thicker due to advection and dispersion processes. At the same time, contaminant concentrations decrease.

There is no data available on groundwater quality monitoring in the areas adjacent to the drilling sumps in the Yukon Territory and Northwest Territories.

In Alberta, approximately 60% of sump fluids tested were found to be toxic (ERCB, 1985). No information could be found on any groundwater quality monitoring in the areas adjacent to these sumps.

Heavy oil developments in the Cold Lake and Peace River areas resulted in very dense well spacing, and large volumes of waste were produced at one location. This forced operators to develop a waste management plan which would assure waste containment and which would be acceptable to various government agencies. In response to this challenge, Shell Canada Limited developed a program that would allow handling of 34,000 m^3 of solid and liquid wastes at its Peace River Expansion Project (PREP). It involved, according to Davies and Wensley (1987), disposal of drilling wastes in the following manner:

1. Either clarifying for reuse or pumping the liquid waste down a disposal well.

2. Removing solids and sludge (approximately 22,000 m^3) from the pits, mixing them with fresh clay till and spreading this mixture on the surface to dry prior to burial in excavated pits. This mixture was placed in the pit, compacted and capped with a minimum of one metre of clay.

3. In the areas of the waste site where the solids and sludges were worked, a 15 cm layer of soil will be removed, placed in excavated pits and capped with a minimum of one metre of clay.

4. The rest of the reclamation process involved spreading the remaining unused clay material on the surface of the site, recontouring the site and spreading topsoil. The final step will be revegetation of the area.

Groundwater quality monitoring conducted to date at the site indicated no signs of contaminant plume development (O'Leary et al, 1988).

Experience gained at PREP indicates the viability of drilling waste disposal in a manner described above. It should be noted however that the success of waste burial will depend greatly on hydrogeology of the selected site. Of equal importance are facility design and field operation techniques.

Although, projects of PREP or Cold Lake magnitude are not contemplated at the present time for the Canadian North, experience gained from operations conducted in other climatic zones may be helpful in development of economically and environmentally acceptable methods of drilling waste disposal.

The American Petroleum Institute sponsored a study on drilling mud pits and produced water impoundments. A general conclusion of this study is that chloride and metal concentrations observed in groundwater return to levels acceptable for drinking water within several hundred feet from investigated facilities. Thus, they do not constitute a health hazard for potential water users (Best, 1985).

According to Oil and Gas Journal (1987), the US EPA addendum to its draft report "Management of Wastes from Oil and Gas Exploration, Development and Production", contained the following statement; "of the

hundreds of chemical constituents detected both in reserve pits and produced fluids, only a few from either source appear to be of concern to human health and the environment via ground and surface-water pathways. The principal constituents of potential concern, based on analysis of their toxicological data, their frequency of occurrence, and their mobility in groundwater include arsenic, benzene, sodium, chloride and mobile salts".

Conversely, studies conducted in Canada's Arctic by Bryant et al (1974) indicate that water base drilling fluids constitute a wastewater with characteristics capable of causing water pollution. Futhermore, such wastes have been demonstrated to be acutely toxic to fish.

7.3 DOWNHOLE DISPOSAL

Downhole injection of drilling waste fluids is not commonly used in Canada. In northern regions, freezing of liquids, limited facilities to conduct physical and chemical analyses of wastes, as well as technical problems associated with removal of suspended solids, practically eliminates use of this disposal method.

Disposal of liquids in deep geological formations is potentially an environmentally attractive method of waste disposal. Under normal circumstances, properly completed exploration wells should allow injection of fluids without potential contamination of the fresh water aquifers or mineral resources. It appears, however, that regulatory constraints, combined with technical problems, make this alternative less favourable than liquids containment in sumps or disposal through land surface applications.

To protect fresh water aquifers prior to downhole drilling liquids disposal, the following aspects should be assessed:

- geological units suitable for subsurface disposal;
- confining conditions (including structural features);
- hydrogeological conditions;
- well construction details; and,
- volume and quality of waste.

Where conditions are favourable for disposal in deep geological formations, it may be assumed that the waste has been removed from circulation, i.e. outside the hydrologic cycle, and will remain in underground storage for a period measured in geological time.

7.4 ABANDONED WELLS

Improperly abandoned boreholes (exploration, production and injection wells) may be considered as potential pathways for liquid/gas migration between geological units. Risks and potential damage to groundwater resources due to unplugged or improperly abandoned wells are high. Brine and saline water, confined in geological strata may move upward to the ground surface through these artifically created hydrogeological windows. In the process of migration, contamination of shallow groundwater may occur and, in extreme cases, discharge of liquids to the ground surface may take place.

To prevent environmental damage, strict regulations controlling well abandonment procedures are in force in Canada. Once a hole is abandoned, there is no practical method to assess the integrity of cement or mud plugs placed in the hole. Only an uncontrolled flow from the

well or a leak appearing in the adjacent area would be an indication of a plug failure. In most other instances, migration between different formations may occur without any indication at the ground surface. To avoid potential problems and reduce potential environmental damage, operators and regulators must pay attention to proper abandonment of wells.

8. POTENTIAL IMPACT OF DRILLING WASTE DISPOSAL ON GROUNDWATER RESOURCES IN PERMAFROST TERRAIN

8.1 GENERAL

The Northwest Territories, with a population close to 50,000, depend mostly on surface water as a source of potable and industrial water. This is due to the abundance of surface water flowing from the Canadian Shield area. At the same time, groundwater availability in the Shield and continuous permafrost areas is limited. In the sedimentary basins, poor chemical quality groundwater occurrences (eg. Pine Point and Lac la Martre areas) are common. This further restricts the potential for groundwater resource development. It is estimated that less than 1 percent of the Northwest Territories population depend on groundwater as a source of water supply.

Sedimentary deposits ranging in age from the Paleozoic Era to the Tertiary Period, where these are represented by rocks capable of storing and transmitting water, may be considered as a potential source of water supply. Restricted recharge, due to low precipitation and the presence of a permafrost layer, reduces groundwater exchange in the bedrock formations. Long residence-time, combined with availability of soluble minerals, leads to an increase in water mineralization beyond the limits considered as suitable for drinking water. Total dissolved solids concentrations in groundwater within deep sedimentary basins may reach 300 kg/m^3, chloride 183 kg/m^3, and as much as 8 kg/m^3 each for bicarbonate and sulphate ions (Williams and Van Everdingen, 1973; Van Everdingen, 1974).

Quaternary alluvial and glacial deposits overlying bedrock may be considered as the main potential source of groundwater in large areas of northern Canada.

The Yukon Territory, with a population in the order of 25,000 is highly dependent on groundwater as a source of water supply. Hydrogeological conditions are favourable for this resource development in this territory. Higher precipitation in the mountains, presence of large valleys filled with thick coarse-grained granular deposits, contribute to the development of high yield groundwater flow systems. This, combined with locally elevated temperatures, makes groundwater a very attractive source of water supply.

High hydraulic gradients, which impose rapid groundwater movement through the permeable deposits, result in the presence of generally potable quality water in the mountain ranges of the Yukon. Shallow water wells (less than 100 m in depth) and numerous springs are used throughout this territory as a major source of water supply. It is estimated that in winter, 90% of potable water used is derived from groundwater. This rate drops to approximately 75% in the summer period, when some utilization of surface water takes place.

8.2 NORTHERN HYDROGEOLOGICAL REGION

8.2.1 Sumps

Factors such as high hydraulic conductivity, coarse-grained alluvial and glacial materials as well as permeable bedrock deposits located within the active zone, may enhance contamination of groundwater by drilling waste liquids seeping from a

sump. A contaminant plume within this suprapermafrost aquifer will migrate in directions determined by the hydraulic gradients toward local drainage features (eg. river, stream or lake).

The presence of contaminants seeping from a sump, through a groundwater circulation system to a local stream, may be environmentally critical during winter when groundwater provides virtually all the flow. Under different scenarios, contaminant transport and concentrations will be controlled by a number of factors. These will ultimately lead to contaminant dilution. A knowledge of local hydrogeological conditions, type and concentration of particular contaminants are required to determine plume development. It would also allow to determine distance at which all contaminants will be attenuated or dispersed to approximate background concentrations.

To reduce the potential for groundwater contamination, a soil mound can be built over a frozen sump. This would ensure the isolation of frozen sump fluids through incorporation in the permafrost. These conditions were observed at the well site Mallik L-38 located in the Mackenzie Delta (Bryant et al, 1974).

Less susceptible to contamination would be groundwater present in the intrapermafrost zone. Presence of taliks in the permafrost region is not a common occurrence, thus occurrence of a drilling waste sump in its proximity is a rather remote possibility. Intrapermafrost aquifers may be present at considerable depth. Thus seepage from a pit would migrate vertically through the unsaturated sediments. In this zone, potential contaminants would be exposed to a range of dispersion, sorption and chemical

transformation processes, leading to contaminant degradation and dilution. The presence of taliks is usually related to major surface water bodies (eg. rivers, lakes). Infiltration of surface water could significantly contribute to contaminant dispersion.

In areas where subpermafrost groundwater is discharging to the ground surface through thawed zones (taliks), contaminants most likely would be restricted to the upper part of intrapermafrost or in the suprapermafrost aquifer. Under opposite (recharging) conditions, contaminants may be introduced through the talik to the subpermafrost aquifer. However, in view of the relatively small volume of contaminants contained in a single exploration well sump, slow release from the pit and high potential for dilution, it is expected that negative environmental impacts will be limited, unless the liquids are of particularly high toxicity.

8.2.2 Downhole Disposal

There have been approximately 1,600 oil and gas exploration and production wells drilled to date in the territories. During drilling, the permafrost around the well may become thawed out. Where groundwater in permafrost is under artesian pressure, a risk of uncontrolled flow is everpresent. Water flowing through the annular zone outside the casing may further degrade the permafrost and remove soil and rock particles, thus leading to an uncontrolled artesian discharge. Subsequent remedial work in permafrost terrain to control such flow is very expensive and technically difficult to accomplish. An interesting case history, related to an uncontrolled flow from a shallow (less

than 40 m deep) water well is described by Linell (1973). Efforts to control the flow and utilize the well were not only expensive, but also took several years to achieve success.

Similar conditions may occur during the oil and gas exploration or production drilling. Therefore, when planning a drilling program, special attention would be placed on maintenance of a permanently frozen contact or impermeable seal between the casing and the permafrost. Otherwise, hydraulic connection may be opened, leading to groundwater migration between different aquifers. This is unacceptable even in instances where the groundwater flow does not reach a full-scale blow-out condition.

These very real possibilities should be taken into account when planning downhole disposal of drilling liquid wastes. Normally, prior to the downhole disposal, liquids should be treated to remove solids and attain biological sterilization. This may require thawing the sump contents. Downhole disposal of elevated temperature liquids (above 0°C) may cause thawing of permafrost as described above. This, combined with attendant pressure increases due to liquids injection, may promote the opening of new underground circulation routes.

Regulators must be concerned with monitoring hole integrity following downhole fluid disposal in the permafrost terrain. Operators are aware of the problems and expense that could be associated with a production well or injection well opening an hydraulic connection permitting artesian water flow. In the process of drilling, producing or injecting, it is impossible, or at least impractical, to maintain a bore hole temperature that

will not cause thawing of the permafrost. Accordingly, it is normal practice to assure that modern casing cementing techniques are utilized to provide a good casing/formation bond in the drilled impermeable sections separating aquifers and/or petroleum reservoirs that one wishes to keep segregated.

9. CONCLUSIONS

Literature review, interviews with the representatives of the industry and governments, and subsequent evaluation lead to the following conclusions:

9.1 SUMPS (SW 3.1)

1. Sumps are most common in drilling waste containment/disposal in the Territories. Experiments conducted to date with on-land disposal of drilling wastes appear to be very encouraging.

2. Information collected indicates that drilling waste disposal in sumps, downhole or on land, has not created major environmental problems to date. Local environmental damage in the area adjacent to the sumps has been observed in a few (less than twenty) cases. The visible areal extent of damage was usually limited. Levels of associated groundwater contamination have not been defined.

   This situation may change when the use of oil based muds becomes an acceptable procedure in permafrost areas. Presence of aromatic hydrocarbons in these types of muds will create a higher potential for significant groundwater contamination in comparison with fresh water or brine based muds.

3. There is practically no information available regarding impact of drilling waste disposal on groundwater resources in both Territories.

4. To date, no hydrogeological studies have been conducted to define the extent and concentration of groundwater pollutants originating from drilling fluids disposal in northern Canada.

5. Approximately 1,600 oil industry wells were drilled in the Territories over the past fifty years. Some limited information exists on less than 20 cases where loss of mud or seepage from the pit negatively affected groundwater quality within the active layer. No groundwater quality monitoring programs documented these incidents.

   From many holes drilled, very little, if any, damage has been observed at these exploration sites.

   The active layer is more susceptible to potential groundwater contamination than intrapermafrost or subpermafrost zones. Intuitively, it may be expected that the possible impact on intrapermafrost or subpermafrost groundwater resources will be minimal, however these expectations have not been demonstrated or proven.

9.2 DEEP WELL DISPOSAL (SW 3.2)

1. Downhole disposal of drilling wastes is not common in northern Canada due to logistical and technical difficulties associated with permafrost and low ambient winter temperatures. There is no published information regarding groundwater contamination from downhole disposal. This should not be construed as proof that this method of waste disposal could not have a negative impact on groundwater quality.

2. Downhole disposal may be an attractive option for waste liquids disposal. Such a disposal, however, may trigger development of thermokarst which may lead to undesirable hydrogeological phenomena (eg. hydraulic communication between different aquifers or venting to the ground surface).

3. Downhole disposal of waste fluids is not in common use because of the high costs associated with liquid treatment and injection.

9.3 ABANDONED EXPLORATION WELLS

1. Improperly abandoned exploration or production wells may allow the migration of liquid and/or gas between geological units. Development of such a situation may have significant impacts on local hydrogeological conditions and possibly on local environment.

9.4 GENERAL GROUNDWATER (SW 3.3)

1. Present knowledge of hydrogeological conditions and available groundwater resources in Yukon and Northwest Territories is very general. Remoteness of the area, low population density and sporadic industrial development are partially responsible for this situation. It should be recognized, however, that groundwater has an important role to fullfill in the Yukon and to a lesser extent, in the NWT. Groundwater discharges provide a baseflow in rivers during winter months. It is a water supply source for the majority of the Yukon Territory and locally in the NWT. Groundwater has an increasing potential as a source of water supply for the mining and other industrial developments.

2. Hydrogeological studies are not only time consuming but are also comparatively expensive. This is especially true when the need to drill in remote areas is taken into account. Constant progress in drilling mud technology means that it is essential to keep pace with present developments. It is impossible to predict the chemical characteristics of new products and their implications for disposal that may be introduced in forthcoming years.

3. Limited knowledge of hydrogeological conditions in the Territories and present low use of groundwater should not be construed as a licence to operate without any restrictions regarding groundwater protection.

4. Existing legislation and regulations concerning protection of the water resources (including groundwater) against pollution from oil and gas industry activities appear to be adequate at this time. In addition, this industry has its own operation, waste disposal and environmental protection guidelines and standards, which in most instances are rigorously followed by the companies involved in exploration activities.

5. Groundwater occurrence, recharge and circulation, as well as potential for contamination in the permafrost area are different from those encountered in temperate climates. Therefore, problems associated with groundwater protection are expected to be different, as well.

   The presence of a frozen, low hydraulic conductivity zone below the active layer, in most instances would be expected to control the vertical extent of potential contamination. Taliks may conduct

contaminants from the active layer downward, toward subpermafrost aquifers. The presence of thawed zones, unlike major aquifers, is very difficult to define. Groundwater recharge and circulation routes are controlled by the presence of frozen soil/rock. In temperate climates, aquifer restoration/contaminant recovery may be conducted all year around. This would not be possible in the case of a suprapermafrost aquifer, which remains frozen during most of the year.

6. In the event of a significant groundwater contamination incident requiring contaminant recovery, costs and logistical problems associated with an effective clean-up may be prohibitive. Accordingly, prevention of groundwater pollution should be a major consideration of all parties involved in the execution and regulation of industrial activities in the North.

10. RECOMMENDATIONS REGARDING GROUNDWATER RESOURCES PROTECTION IN CANADA COLD REGIONS WITH HYDROCARBON POTENTIAL

10.1 RESEARCH RELATED TO DESIGN, CONSTRUCTION, OPERATION AND ABANDONMENT OF DRILLING WASTE CONTAINMENT/DISPOSAL FACILITIES.

10.1.1 General

1. In order to assist petroleum industry and government field staff in the selection of an optimum location and method for environmentally safe disposal of drilling wastes, the development of a field manual should be considered. Pedology Consultants et al. (1986) prepared a field manual on "Disposal of Wastes From Drilling Systems on the Public Lands of Alberta". This document should be adopted for different climatic, geologic, permafrost and hydrogeologic conditions in the Territories.

2. Research in drilling systems continues to develop fluids which would increase drilling progress. It appears, however, that environmental concerns are considered to be of lesser importance to producers.

   Some pressure should be exerted on drilling fluid manufacturers and incentives offered to operators to develop and use fluids suited for recycling (eg. polymer muds). This would reduce or eliminate the volume of liquid wastes disposed to a sump or onto the land. In cases where sump development is very expensive, recycling may prove to be more cost effective than sump disposal.

3. Restrictions on drilling waste containment/disposal procedures should be decreased by imposing a ban on the use of certain chemicals which were established to have negative environmental impacts. This procedure would be similar to that adopted for offshore operations where mud systems are routinely disposed of in the ocean, provided they have been kept free of certain organic compounds or heavy metals. In conjunction with this, a review of sampling and toxicity testing methods should be completed. The operation permit for sump treatment and abandonment should specify testing and treatment methods.

   The operator in his site reclamation plan should make provision for the assessment of the potential impact of drilling wastes disposal on groundwater resources. Mitigative measures should be developed for all contingencies. A plan should be followed to combat any contaminant problem. The operator should be made responsible for potential damages to groundwater resources.

10.1.2 Sumps

1. Except for the specific extraction-exploration activities associated with the Norman Wells and Pointed Mountain fields in the NWT, most of the petroleum exploration undertaken to date has been in relatively cold permafrost in the Mackenzie Delta area and the arctic islands. Because of the generally low ground temperatures in these regions, the presence and operation of sumps is not likely to cause an extensive thermokarst development. However, this is not the case in

"warm" permafrost, which is generally defined as having a mean annual near surface temperature with approximately 2 - 3° of the freezing point. "Warm" permafrost exists south of approximately Norman Wells in the MacKenzie Valley.

In warmer permafrost, the effect of surface disturbance and disposed waste materials in a sump on increased absorption of solar radiation can increase the ground temperatures and result in extensive thermokarst development. In the presence of masses of ground ice, the sump can be expected to subside and flood, with attendant increased absorption of solar radiation and related ground warming. The area around and south of Norman Wells is known to have undergone thaw depths in the range of up to 15 m or more, where the ground surface has been disturbed. The impact of such a depth of thaw occurring beneath a sump could affect groundwater.

The authors are not aware of any thermal modelling performed to predict the potential extent of thaw around a sump for a range of soil, ice, ground temperature and surface conditions. It is therefore proposed that a sensitivity study be conducted to determine the theoretical impacts for a range of ground conditions in warm and cold permafrost, which could then be related to the different geographic regions of the Yukon and NWT in which petroleum exploration is or may become active. The thermal modelling should be performed in conjunction with the proposed hydrogeological laboratory and modelling activities discussed in Section 10.2.2.

2. The petroleum industry has concerns regarding the environmental impact of exploration drilling and associated activities.

Exploration costs in permafrost terrain are very high. Most of the time and expense is usually invested in program planning and logistics, however, little emphasis is placed on sump site selection. Since most of the drilling is done in the winter, sumps are sited and constructed at that time. A site selection investigation should take place in summer, when all ground features are clearly visible. This would assist in a better sump location, from the hydrogeological point of view. Review of factors such as soil/rock hydraulic conductivity, depth to groundwater surface, location in relation to groundwater discharge/recharge areas would certainly help in site selection optimization. Thus the potential for impact on the groundwater regime would be reduced. Regulators should encourage operators to accept this principle where justified by concerns over groundwater.

10.1.3 Downhole Disposal

1. Downhole disposal should be considered as an alternative to sump and land disposal during summer drilling operations. In general, it is an attractive method for waste disposal and isolation. Its applicability to permafrost areas should be investigated. Development of thermokarst around the borehole is a factor of which drilling operators are aware. Modern drilling/cementing techniques normally preclude hydraulic connection between different groundwater bearing strata.

10.1.4 Land Disposal

This method of drilling waste disposal was experimented on in the High Arctic. No sump was utilized, drilling fluids were permit-

ted to drain into an adjacent creek, and the environmental effects were measured for several years following well abandonment. Groundwater quality monitoring was not included in these experiments. The environmental disturbance resulting from land disposal in permafrost areas may, in many instances, be smaller than those resulting from sump building and the later "squeezing" of the sump (at which time the contained fluids most often find their way into local drainage systems anyway).

The potential for land disposal during summer months should be investigated, especially given that waste treatment or dilution is more feasible during summer than during winter.

10.1.5 Alternate Disposal Methods

With respect to oil based muds, consideration should be given to research related to treatment methods such as incineration or solidification. The studies should assess mitigative applicability and cost effectiveness and also specify conditions for the site specific application of each method.

10.2 HYDROGEOLOGICAL RESEARCH REQUIRED

10.2.1 Regional Aspects

1. Groundwater demands will be a controlling factor in the exploration and development of this valuable resource in the Territories. The size of the Yukon and Northwest Territories makes it prohibitively expensive to conduct a baseline hydrogeological study. Therefore, a maximum effort should be

directed toward the accumulation and storage of information useful to hydrogeology resulting from various activities (eg. mining, inventory of all new wells drilled in the area, and springs and icings observed during road and/or pipeline construction). The regulators should consider creating such an information bank and promote free exchange of information.

2. An inventory of the drilling waste sumps should be useful in dealing with any future environmental impact assessments related to these sumps. Data on volume of drilling liquids, additives and their quantities, mud system used, as well as containment/disposal procedures, should be collected from operators. This would allow a first stage assessment of potential environmental impacts at each site. This phase should be followed either by site visits to selected sites or airphoto interpretation (if coverage is available). Based on archival data and field reconnaissance, closer assessment would identify sites that would be conducive/suitable for further hydrogeological studies, if justified.

3. In a study of groundwater availability in a permafrost region, a knowledge of aquifer recharge from precipitation or surface water infiltration is needed. Clearly, the amount of groundwater pumped from an aquifer in the long-term cannot exceed the long-term recharge rate. Recharge via infiltration is influenced by such factors as amount of rainfall, evapotranspiration, surface runoff and soil moisture. Recharge and component factors have been studied extensively in temperate latitudes. It is an elusive parameter to

quantify as it is very site-specific, both climatically and geologically. The availability of good quality historic information on meteorological parameters and surface and subsurface hydrological data is usually essential. However, intergranular infiltration can be circumvented under certain geologic conditions (eg. karst terrain, desiccation cracks), leading to rapid recharge. Some of these considerations may be applicable to arctic and sub-arctic environments. Research on determining and quantifying recharge mechanisms which apply to northern environments would therefore be useful. This could be done by conducting a hydrologic budget study on a well defined northern aquifer, which presently is utilized as a source of water supply for a community or industrial complex.

4. A number of potential environmental problems may arise from the inappropriate disposal of drilling wastes. Individual environmental concerns are certainly important in themselves (e.g. damage to plant life), however all environmental aspects must be considered as one interrelated system. In this way, it should be possible to achieve a fuller understanding of causes and thus anticipate effects. For example, contamination of soil by drilling waste may not only cause damage to the flora in the affected area, but may also lead to surface water and groundwater pollution.

   To date, most studies have concentrated on the evaluation of drilling waste disposal impacts on soil and plant life. A study which would incorporate surface and groundwater quality for a selected sump area could shed new light on contaminant migration processes. Potential impacts on water quality are conventional environmental concerns.

7. Groundwater is a valuable renewable resource. Proper technical and economic development of this resource cannot take place without a knowledge of hydrogeological conditions, which includes information on both groundwater occurrence and quality. The regulators and especially water resources managers should place a great emphasis on development of a regional hydrogeological data bank. This information would be useful for further development of the available groundwater resources and their protection against potential contamination.

10.2.2 Specific Aspects Related to Drilling Waste Containment/Disposal

1. In order to develop procedures for handling toxic muds, it would be valuable to define migration conditions, extent of contaminant plume, contaminant concentration and gradients at abandoned sumps located within permafrost. Sumps which were classified as seeping contaminants based on soil sampling or geophysical tests should be investigated first. Examples of sumps which could be considered for this type of hydrogeological exploration would be sumps B53 (Norman Wells area), D52 and D20 in the Inuvik and Tuktoyaktuk areas, respectively.

2. In view of the high expense of any field exploration program in the north, it may be possible to conduct laboratory experiments to simulate field conditions. This would allow assessment of various contaminant behavioural phenomena (eg. sorption, biological and chemical degradation) in the permafrost environment. The laboratory results could be verified by comparison with field exploration programs. If the

results are comparable, simulation methods would become a valuable tool in assessment of potential environmental impact. It should be noted, however, that field verification is vital and cannot be completely replaced by laboratory or computer modelling.

3. A number of studies have been conducted on different aspects of drilling waste disposal in permafrost areas. Most of them have identified the potential for groundwater contamination. No studies related to groundwater quality at drilling waste disposal facilities have been conducted to date. When a future environmental study is contemplated, its scope should include groundwater quality monitoring around the sump. To expand the scope of such a study, it would be further advantageous to select a nearby plot for land disposal of liquids. Monitoring would allow comparison of the impact that each disposal method had on groundwater quality. A more general assessment would require a multi-disciplinary study covering all aspects of groundwater, surface water, soil chemistry and biology.

Respectfully submitted,
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APPENDIX I

LIST OF GOVERNMENT CONTACTS;
DRILLING FLUIDS MANUFACTURERS AND
DISTRIBUTORS IN CALGARY, ALBERTA;
LIST OF ACRONYMS

LIST OF GOVERNMENT CONTACTS

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Gerry Whitley, INAC, Administer Pollution Control.

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Baroid of Canada, Harold Hanson.
Canadian Fluid Systems Ltd., Larry Pamplin.
Concord Drilling Fluids Ltd., Dick Kambach.
International Drilling Fluids, Brian Twindells.
M-1 Drilling Fluids Canada Inc., Garth Faribrother.
Milpark Drilling Fluids, Brian Dick.
Technifluids NMC, Dan Williamson.

LIST OF ACRONYMS

ADEC	Alaska Division of Environmental Conservation
AOGCC	Alaska Oil and Gas Conservation Commission
AENR	Alberta Energy and Natural Resources
AE	Alberta Environment
API	American Petroleum Institute
COGLA	Canadian Oil and Gas Lands Administration
CPA	Canadian Petroleum Association
ERCB	Energy Resources Conservation Board
EPA	Environmental Protection Agency
EPS	Environmental Protection Service
GSC	Geological Survey of Canada
INAC	Indian and Northern Affairs Canada
NIWA	Northern Inland Waters Act
NWT	Northwest Territories
YT	Yukon Territory